Quantification of the Long-Term Benefits of On-Site Erosion Detention for Developing Austin Watersheds:

Stream Protection Curve

March 2011

HDR | ONE COMPANY *Many Solutions®*

In association with:

Kurkjian Engineering Corporation

Quantification of the Long-Term Benefits of On-Site Erosion Detention for Developing Austin Watersheds:

Stream Protection Curve

Prepared for:

Prepared by:

ONE COMPANY
Many Solutions

HDR Engineering, Inc.

Texas Firm Registration No. F-754 (Expires 8/31/2011)

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March 2011

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March 7, 2011

Mr. Morgan Byars, P.E.
Watershed Protection & Development Review Department
Stream Restoration Program
City of Austin
P.O. Box 1088
Austin, TX 78767

Re: Quantification of the Long-Term Benefits of On-Site Erosion Detention for Developing Austin Watersheds: Stream Protection Curve – Report QA/QC Review
CIP No. 6039.021

Dear Mr. Byars:

I have reviewed the report entitled "Quantification of the Long-Term Benefits of On-Site Erosion Detention for Developing Austin Watersheds: Stream Protection Curve" dated March 2011. I am a licensed professional engineer in the State of Texas. My QA/QC review was conducted in accordance with the QA/QC Policy of HDR Engineering, Inc. My review of the Engineering Report included the following elements:

1. Recommendations based on data presented;
2. Report form and content; and
3. Understandability by City management and third parties.

If you have any questions, or require additional information, please call me at 912-5100.

Sincerely,

HDR Engineering, Inc.

Eric J. Stewart
Texas P.E. No. 95907

cc: Scott M. Muchard, P.E., HDR Engineering, Inc.

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Executive Summary

At the request of The City of Austin (COA) Watershed Protection and Development Review Department (WPDRD) HDR Engineering, Inc. (HDR) and Kurkjian Engineering Corporation (KEC) have continued the erosion detention study entitled "Quantification of the Long-Term Benefits of On-Site Erosion Detention for Developing Watersheds"[1] with a third phase. The first two phases of the project, conducted by HDR in association with Glenrose Engineering, Inc. and KEC, and completed in March 2005 and January 2007, explored the effectiveness of various detention pond designs in controlling erosion in Austin stream channels. The third phase of the study, described herein, used the methodologies demonstrated in the previous work to identify a stream protection (erosion prevention) pond volume design criterion for which post-development erosion index values match the predevelopment values. The stream protection volume criterion is expressed as a curve relating required pond storage volume to watershed percent impervious cover, specifying the required volume to be captured and released over a 48-hour period.

The curve was developed through long-term continuous simulation (LTCS) modeling of ponds with various volumes controlling runoff from hypothetical 100-acre watersheds having a range of impervious cover levels. As with the previous work, the LTCS were performed using the U.S. Environmental Protection Agency's (EPA) Storm Water Management Model (SWMM) software. The LTCS pond discharge hydrographs were input to a FORTRAN program that computed the channel hydraulics and resulting erosion index values. The erosion index values indicate stream erosion potential and were used to estimate, for the range of impervious cover levels, the pond volume that would produce an erosion index value matching pre-development conditions.

Figure ES-1 shows the stream protection curve with the pond volume expressed as a depth of watershed runoff. The COA 1/2 inch plus 1/10th inch standard water quality volume[2] is also plotted in Figure ES-1. Comparing the two curves suggests that the COA standard volume provides more storage than is necessary to match predevelopment erosion potential as quantified

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[1] HDR Engineering, Inc in association with Kurkjian Engineering Corporation, *Quantification of the Long-Term Benefits of On-Site Erosion Detention for Developing Austin Watersheds*, January 2007.

[2] The COA standard water quality volume is the first 1/2 inch of runoff plus an additional 1/10th inch for each 10% increase of gross impervious cover over 20% within the drainage area to the control.

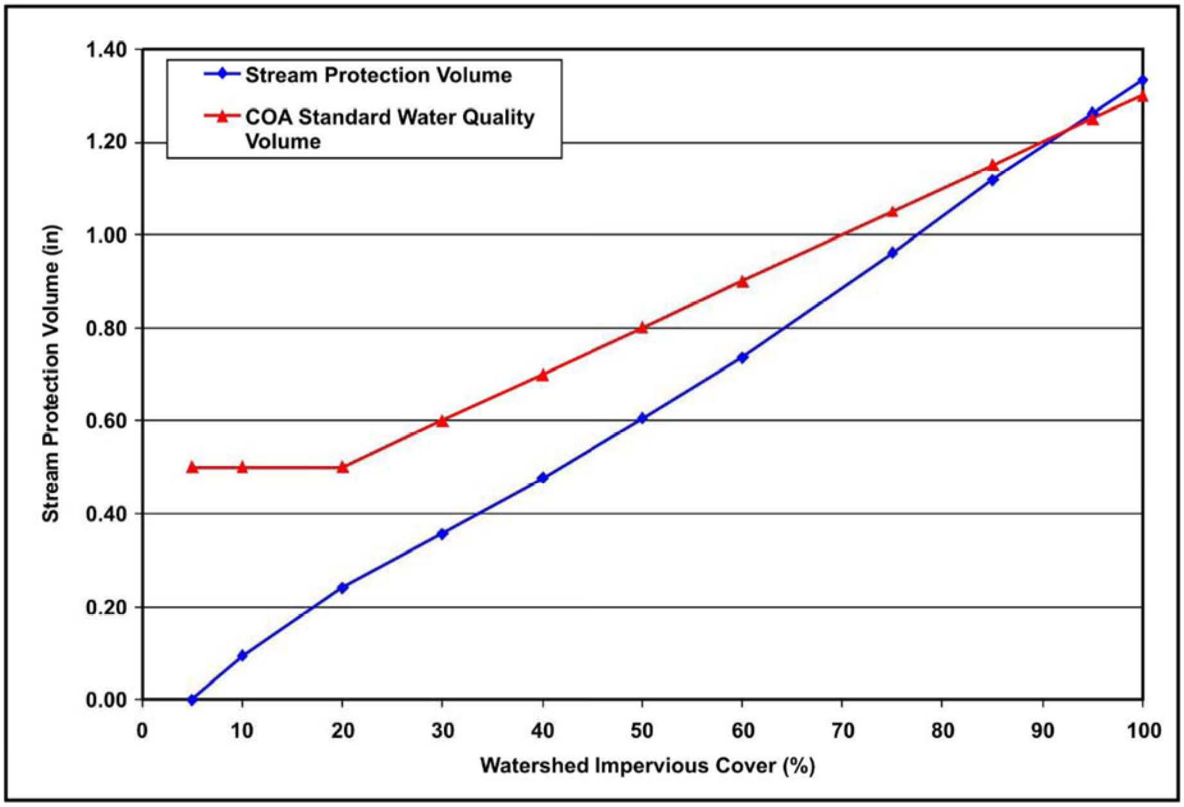

Figure ES-1. Stream Protection Curve Compared to COA Water Quality Volume

by the excess stream power (ESP) erosion index for all but the highest levels of impervious cover (above approximately 92%). The current results differed from the previous two phases, which indicated that the COA standard water quality volume may provide more protection than is necessary at impervious cover levels less than approximately 50% and less protection than is necessary at impervious cover levels greater than approximately 50%.

The variation in the third phase results is related primarily to a change that was made in the SWMM model watershed response. In previous study phases, the SWMM model was "calibrated" to approximate the 3-hour design storm hydrograph produced by a single-event model that uses the Natural Resources Conservation Service (NRCS) curve number and unit hydrograph methodologies. In the third phase, the 3-hour design storm was replaced with a 24-hour design storm in order to be consistent with current City criteria. Recalibrating the SWMM model to the longer event required the infiltration parameters to be modified to produce less infiltration and more runoff. As a result, the erosion potential of the uncontrolled watersheds increased compared to the previous phases of the study. The relative increase in erosion potential was greater for the undeveloped watershed than for the developed watersheds, which is consistent with the infiltration parameters only affecting the pervious portion of the watershed; changing these parameters has less of an effect on watersheds with less pervious cover. The effect of the greater increase in erosion potential for the undeveloped watershed was that with the 24-hour calibration, detention ponds need to do less to mitigate the estimated watershed runoff erosion potential to predevelopment levels. As a corollary of this, a pond of a given volume would be expected to show better performance in terms of its ability to reduce ESP values to the pre-developed condition when evaluated with the 24-hour calibration than when evaluated with the 3-hour calibration.

The stream protection curve shown in Figure ES-1 was developed based on assumptions regarding the watershed characteristics, receiving channel characteristics, rainfall event, and pond design. The sensitivity of the curve to all significant variables has not been quantified. Therefore, generalizing the curve for use in situations that do not conform to the assumptions used in its development may not produce reliable estimates of the required stream protection volume. Should the City have an interest in pursuing further work on quantifying the long-term benefits of on-site erosion detention, it is recommended that effort be focused on assessing the generalized applicability of the stream protection curve; i.e., whether the curve can be applied to cases that deviate from the specific assumptions upon which it is based. Areas for potential further investigation are elaborated upon in Section 5.

Section 1
Introduction

1.1 Background

At the request of The City of Austin (COA) Watershed Protection and Development Review Department (WPDRD) HDR Engineering, Inc. (HDR) and Kurkjian Engineering Corporation (KEC) have continued the erosion detention study entitled "Quantification of the Long-Term Benefits of On-Site Erosion Detention for Developing Watersheds"[3] with a third phase. The fist two phases of the project, conducted by HDR in association with Glenrose Engineering, Inc. and KEC, and completed in March 2005 and January 2007, explored the effectiveness of various detention pond designs in controlling erosion in Austin stream channels.

In the previous work, a hypothetical 100-acre developing watershed was utilized as a test case. Standard design storm hydrologic analysis (TR-20 modeling) was utilized to design six different types of facilities, with a facility of each type being designed for each of three watershed post-development impervious cover percentages: 20%, 50%, and 75%. Analyses of several of the facility types included the examination of both 48- and 72-hour release durations. Overall, a total of 66 different facilities were designed and modeled.

The long-term response of each facility was evaluated using long-term continuous simulation (LTCS) modeling. A model of the hypothetical watershed was developed utilizing a 15-year rainfall record (1990-2004) with the U.S. Environmental Protection Agency's (EPA) Storm Water Management Model (SWMM) software. The SWMM model was "calibrated" to the TR-20 model by adjusting parameters within reasonable tolerances such that the post-development runoff hydrographs from the 2-year and 100-year design storms approximated the TR-20 hydrographs used to design the stormwater facilities.

The stage-storage-discharge ratings for each detention facility were input into the SWMM model and the post-development watershed discharges were routed through each facility, producing a long-term (15-year) series of pond outflow reported on a 15-minute time interval. Hydraulic parameters, shear stress, and excess shear stress were computed at each time-step for a receiving channel sized to convey the 2-year pre-development peak discharges at near bankfull stage. Two alternative bed materials composed of medium gravel (15 mm) and very

[3] HDR Engineering, Inc in association with Kurkjian Engineering Corporation, *Quantification of the Long-Term Benefits of On-Site Erosion Detention for Developing Austin Watersheds*, January 2007.

coarse gravel-sized (37.5 mm) particles were assumed. Preliminary work also examined a receiving channel sized to convey the 10-year pre-development peak discharges at near bankfull stage and included analysis of a sand bed receiving channel.

The performance of each pond was evaluated by computing two erosion indices that reflect the cumulative impacts of all flows in the receiving channel: cumulative excess shear stress (ESS) and cumulative excess stream power (ESP). Among the findings of the study was that the standard COA water quality capture volume was adequate to control erosion (and in some cases over-controlled) for low assumptions of percent impervious cover (20%), but for watersheds with high levels of impervious cover (75%) the capture volume was too small to mitigate the increased runoff from development.

1.2 Project Approach

The third phase of the study, described herein, used the methodologies employed in the previous work to identify a stream protection (erosion prevention) pond volume design criterion for which post-development erosion index values match the predevelopment values. The stream protection volume criterion is expressed as a curve relating required pond storage volume to watershed percent impervious cover, specifying the required volume to be captured and released over a 48-hour period. The curve was developed through LTCS modeling of ponds with various volumes controlling runoff from hypothetical 100-acre watersheds having a range of impervious cover levels. As with the previous work, the LTCS were performed using the EPA SWMM model. The LTCS pond discharge hydrographs were input to a FORTRAN program that computed the channel hydraulics and resulting erosion index values. The erosion index values were used to estimate, for the range of impervious cover levels, the pond volume that would produce an erosion index value matching pre-development conditions.

Section 2
Pond Design

2.1 Objective of Pond Design Task

The objective of the pond design task was to produce designs that would be subjected to LTCS modeling, with the resulting ESP erosion index values being used to generate a final stream protection curve. The pond designs were based on target storage volumes as opposed to criteria related to a design storm event. The pond outlet works were sized such that the full ponds emptied to 5% of their full capacity in 48-hours. This design approach is similar to that of the ponds evaluated in the previous work that addressed only water quality criteria and release duration without attempting to match pre- and post-development peak discharge rates.

2.2 Preliminary Stream Protection Curve

A preliminary stream protection curve, indicating required runoff capture volume as a function of impervious cover, was developed based on the results of the previous work. This curve served as a guide in selecting the pond volumes that were modeled with LTCS and used to prepare the final stream protection curve.

While previous work evaluated both the excess shear stress (ESS) and ESP erosion index values, the ESP index was used as the basis for evaluating erosion potential in the third phase of the study. In the previous study phase, relative pond performances were found to be similar whether measured by ESP or ESS, and many of the study findings were therefore summarized only by the ESP value.

Erosion index values for various pond designs were computed in the previous phase of the study using contributing watersheds having 20%, 50%, and 75% impervious cover. Based on those results, the pond volume producing an erosion index value approximating that of the undeveloped, uncontrolled (no pond) watershed, referred to here as the "preliminary stream protection volume," was estimated for each of the three impervious cover levels. ESP results for three pond designs: the Save Our Springs water quality pond, 1/2 inch plus 1/10th inch water quality pond[4], and 1-year 3-hour initial abstraction difference pond, all with 48-hour drawdown time, were used to interpolate the preliminary stream protection volume at each impervious cover

[4] The COA standard water quality volume is the first 1/2 inch of runoff plus an additional 1/10th inch for each 10% increase of gross impervious cover over 20% within the drainage area to the control.

level. Of the various designs studied in the previous work, the ESP results for these ponds were considered because they capture a specified runoff volume and release it over a 48-hour period, as opposed to matching a pre-development hydrograph.

The preliminary stream protection volumes at the 20%, 50%, and 75% impervious cover levels were then used to interpolate and extrapolate a preliminary stream protection curve for impervious cover levels ranging from 5% to 100%. This curve is shown in Figure 2-1. Although the curve is based on the results of the previous work, it is considered preliminary for two reasons. First, in the previous work, SWMM parameters were calibrated to 3-hour design storm events, while in the current phase of the study, SWMM parameters were calibrated to 24-hour design storm events. SWMM calibration is discussed in more detail in Section 3.3. Second, the preliminary curve lacks definition in that it is based on pond ESP results at only three impervious cover levels, 20%, 50%, and 75%.

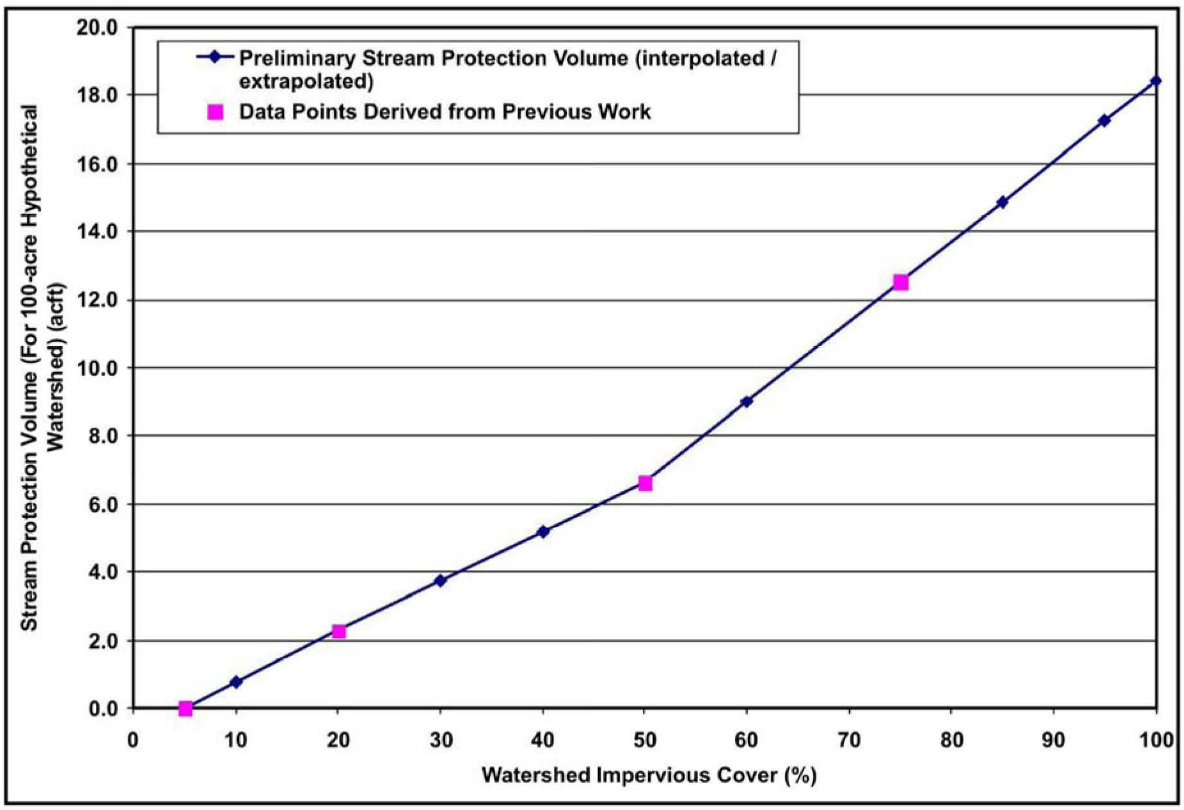

Figure 2-1. Preliminary Stream Protection Curve for 100-acre Developing Watershed

Based on the preliminary stream protection curve, a range of pond volumes at each impervious cover level of 10%, 20%, 30%, 40%, 50%, 60%, 75%, 85%, 95% and 100% were selected. The selected pond volumes, 48 in total, ranged from 50% to 115% of the preliminary stream protection volume and are listed in Table 2-1. These pond volumes were then used as the basis for 48 pond designs that were subjected to LTCS. The pond volumes were chosen so that they would be likely to produce ESP values bracketing the undeveloped, uncontrolled value and could therefore be used to reliably estimate by interpolation the volume that would be required to match the undeveloped ESP value.

Table 2-1.
Pond Volumes

Pond ID	*Pond Vol (acft)*	*Pond ID*	*Pond Vol (acft)*	*Pond ID*	*Pond Vol (acft)*
10% IC 70% Vol	0.53	50% IC 70% Vol	4.64	85% IC 70% Vol	10.41
10% IC 85% Vol	0.64	50% IC 85% Vol	5.63	85% IC 85% Vol	12.65
10% IC 95% Vol	0.72	50% IC 95% Vol	6.30	85% IC 95% Vol	14.13
10% IC 115% Vol	0.87	50% IC 115% Vol	7.62	85% IC 115% Vol	17.11
20% IC 70% Vol	1.59	60% IC 60% Vol	5.39	95% IC 50% Vol	8.62
20% IC 85% Vol	1.93	60% IC 70% Vol	6.29	95% IC 60% Vol	10.34
20% IC 95% Vol	2.16	60% IC 85% Vol	7.64	95% IC 70% Vol	12.06
20% IC 115% Vol	2.62	60% IC 95% Vol	8.54	95% IC 85% Vol	14.65
30% IC 70% Vol	2.61	60% IC 115% Vol	10.33	95% IC 95% Vol	16.37
30% IC 85% Vol	3.17	75% IC 60% Vol	7.51	95% IC 115% Vol	19.82
30% IC 95% Vol	3.54	75% IC 70% Vol	8.76	100% IC 50% Vol	9.21
30% IC 115% Vol	4.29	75% IC 85% Vol	10.64	100% IC 60% Vol	11.05
40% IC 70% Vol	3.62	75% IC 95% Vol	11.89	100% IC 70% Vol	12.89
40% IC 85% Vol	4.40	75% IC 115% Vol	14.40	100% IC 85% Vol	15.65
40% IC 95% Vol	4.92	85% IC 50% Vol	7.44	100% IC 95% Vol	17.49
40% IC 115% Vol	5.95	85% IC 60% Vol	8.93	100% IC 115% Vol	21.18

Note: Pond identification numbers indicate the watershed impervious cover percentage for which the pond was designed and the pond's volume as a percentage of the preliminary stream protection volume.

2.3 Pond Stage-Storage-Discharge Tables

Pond stage-storage-discharge tables were produced for each of the 48 pond volumes identified with the preliminary stream protection curve. The ponds were designed with a square base, vertical sides, and a circular orifice outlet. The pond depth was held constant at 4 ft and the base area was sized to obtain the desired volume.

Pond orifice sizes were calculated using the equation for orifice discharge under falling head.[5]

$$a = 2*A*(\sqrt{h_1}-\sqrt{h_2})/(C*t*\sqrt{(2*g)}) \quad (1)$$

Where:

- a = orifice area (ft^2);
- A = pond area (ft^2);
- h_1 = initial pond depth = 4 ft; and
- h_2 = final pond depth = 0.2 ft;
- C = coefficient of discharge = 0.6;
- t = drawdown time (seconds) = 48 hours = 172,800 seconds; and
- g = acceleration due to gravity (32.2 ft/sec^2).

With Equation (1) and the identified pond volumes, an orifice size was calculated for each of the ponds such that the pond would empty 95% of its volume in 48 hours with no contributing runoff from the watershed.

After computing the pond area and orifice size, pond stage-storage-discharge tables were prepared. A summary of the pond stage-storage-discharge tables is presented in Appendix A. In the tables, orifice outflow as a function of stage was calculated using Equation (2), assuming a free outfall:

$$Q = C*A*(2gH)^{1/2} \quad (2)$$

Where:

- Q = orifice outflow (cfs);
- C = coefficient of discharge= 0.6;
- A = effective orifice area (ft^2);
- g = acceleration due to gravity (32.2 ft/sec^2); and
- H = orifice head (ft).

The resulting stage-storage-discharge tables were input to SWMM for use in the LTCS.

Because runoff volumes produced during the LTCS could potentially exceed the storage volume in the 4-ft deep pond, an overflow area with 3:1 (horizontal to vertical) side slopes was

[5] Brater, E.F., and H.W. King, *Handbook of Hydraulics for the Solution of Hydraulic Engineering Problems*, Sixth Edition, McGraw-Hill Book Company, New York, 1976.

assumed to extend 10 ft above the 4-ft deep pond. The configuration of the pond and overflow area is depicted in the schematic shown in Figure 2-2. The depth of the overflow area was sufficient to ensure that the total capacity of the pond and overflow area was not exceeded during the LTCS (i.e., no water was lost out of the system due to overflow). The overflow area included a 30-ft long overflow weir to release water that exceeded the four-foot pond depth. Discharge from the overflow weir was computed using Equation (3) assuming a free outfall and was added to the orifice discharge when the total depth of stored water exceeded 4 ft:

$$Q = C*L*H^{3/2} \tag{3}$$

Where:

Q = weir outflow (cfs);
C = assumed weir coefficient = 3.0;
L = length of the weir, (= 30 feet in this case); and
H = pond stage (ft).

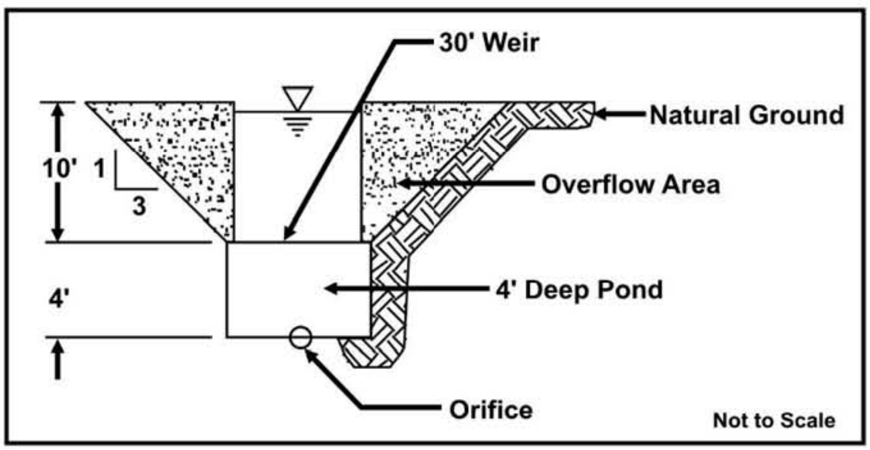

Figure 2-2. Schematic of Pond and Overflow Area

Section 3
Long-Term Continuous Simulation Modeling of Ponds

3.1 Long-Term Continuous Simulation Modeling Overview

Each of the 48 pond designs described in Section 2 was subjected to LTCS hydrologic modeling. Watersheds having 10%, 20%, 30%, 40%, 50%, 60%, 75%, 85%, 95%, and 100% impervious cover were modeled, with the modeling of each watershed including the associated ponds. The 5% impervious cover watershed without a pond, considered to be the undeveloped condition, was also modeled. The erosion index values computed for the various ponds were compared to that of the undeveloped watershed to assess whether the ponds over- or under-controlled erosion relative to undeveloped conditions.

The LTCS modeling was conducted using EPA SWMM Version 5.0.013, which is a later version than that used in the previous work (Version 5.0.007). The SWMM model watershed parameters were calibrated to produce single-event hydrographs that resembled those computed with models that utilize the U. S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) runoff curve number and unit hydrograph methodologies. The long-term pond discharge hydrographs computed by SWMM were then input to a FORTRAN code that computed the ESP erosion index values.

3.2 Long-Term Continuous Simulation Model Description

3.2.1 Model Structure

The SWMM model employed for the third phase of the study was similar to that of previous work and consisted of four elements. A rain gage element was used to store a long term rainfall record, which is discussed in Section 3.2.4, and supply rainfall to a watershed element. The parameters of the watershed element represented a hypothetical 100-acre watershed, which is described in Section 3.2.2. Runoff from the 100-acre watershed flowed directly to a storage node representing the pond. At this node, 48 different pond configurations were simulated with the stage-storage relationships described in Section 2. The ponds were assumed to be empty at the beginning of the LTCS. Outflow from the ponds was routed through a model link which represented the orifice and weir outfall designed for each pond. This outlet link was defined with the pond-specific stage-discharge rating tables described in Section 2. Channel hydraulics were computed outside of SWMM with the FORTRAN program used to compute the ESP erosion index values, making a channel link unnecessary in the SWMM model.

A 5-minute time step was used in SWMM for the majority of the ponds, with a 1-minute time step being used on several smaller ponds to improve pond routing and obtain a smooth outflow hydrograph. All simulations results were reported at 15-minute time intervals, and these 15-minute results were used in the erosion index computations.

3.2.2 Hypothetical Watershed

Hypothetical watersheds with area of 100 acres and impervious cover levels ranging from 5% to 100% were simulated in the LTCS. Several small drainage areas in the upper third of the Walnut Creek watershed were considered during the previous study phases to identify the 5%, 20%, 50%, and 75% impervious cover watershed parameters, which are summarized in Table 3-1. Runoff curve numbers were calculated assuming soils in Hydrologic Soil Group C. The 100% impervious cover watershed was added for the third phase, with parameters based on assumptions similar to those used to develop the parameters for the other impervious cover levels. The 100% impervious cover runoff curve number was taken from Table 2-8 in the *City of Austin Drainage Criteria Manual*.

Table 3-1
Hydrologic Parameters for Hypothetical 100-Acre Watershed

Parameter	Pre-Development	Post-Development			
Impervious Cover	5%	20%	50%	75%	100%
Runoff Curve Number	74	79	86	92	98
Time of Concentration	50 min	30 min	30 min	30 min	17 min

The runoff curve numbers and times of concentration summarized in Table 3-1 are associated with the NRCS excess precipitation and unit hydrograph methodologies commonly employed in single-event models. The NRCS curve number methodology has limitations associated with its use in long-term hydrologic modeling. In addition, runoff hydrographs in SWMM are not generated using the NRCS unit hydrograph methodology. Therefore, the methodologies employed in the SWMM LTCS were different than those that would commonly be used in modeling a single design storm event. This required calibration of the SWMM model parameters to those listed in Table 3-1 as described in Section 3.3.

3.2.3 Receiving Channel

Receiving channel hydraulics, including velocity and shear stress values for each 15-minute time increment in the LTCS period, were computed from the pond outflow hydrographs generated in the SWMM LTCS. The receiving channel characteristics were developed during the previous phases of the study. The geometry of the receiving channel is summarized in Table 3-2. The channel is sized to convey the 2-year pre-development peak discharges at near bankfull stage. The channel bed material is composed of medium gravel-sized particles (15 mm). A discharge-velocity-shear-depth rating table for the 2-year channel was developed during the previous work.

Table 3-2.
2-Year Receiving Channel Characteristics

2-Year Pre-Development Discharge	66 cfs
Bottom Width	4 ft
Channel Depth	2 ft
Side Slopes	2:1
Channel Slope	0.01 ft/ft
Channel Hydraulic Roughness	0.035
Floodplain Hydraulic Roughness	0.075
Floodplain Bottom Width (including channel)	312 ft
Floodplain Valley Side Slopes (H:V)	4:1
Froude Number at Bankfull Discharge	0.74

In addition to the medium gravel receiving channel, the previous work also considered a very coarse gravel (37.5 mm) receiving channel. The results showed that the very course gravel erosion index values varied little, making differences in the pond performances less evident. Preliminary work conducted for the previous phases of the study also examined a receiving channel sized to convey the 10-year pre-development peak discharges at near bankfull stage, and included analysis of a sand bed receiving channel. Early analysis showed that the erosion indices calculated for the 2- and 10-year receiving channels were almost identical. The sand channel was not considered further because the net transport of sand bed material is virtually unavoidable with its low incipient motion discharges.

3.2.4 Precipitation and Evaporation

The 15-year (1990 – 2004) continuous precipitation record of 15-minute values developed from the COA Flood Early Warning System (FEWS) Gage 2240 in the previous work served as the long-term precipitation record for the third phase. The monthly average evaporation rates developed during the previous work, summarized in Table 3-3, based on Camp Mabry weather station records from 1979 to 1996 were also utilized.

Table 3-3.
Monthly Average Evaporation Rates (inches/day) at Camp Mabry (1979-1996)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.18	0.23	0.28	0.30	0.28	0.28	0.26	0.20	0.15	0.14	0.13	0.15

3.3 Calibration of SWMM to TR-20

3.3.1 Purpose of Calibration

SWMM model parameters were adjusted so that the singe-event design storm runoff hydrographs (2-year and 100-year events) produced by SWMM approximated those produced by the NRCS TR-20 model. The TR-20 model includes methodologies commonly used in hydrologic analyses conducted for land development, such as the NRCS curve number and unit hydrograph methods, while SWMM has long-term simulation capabilities but uses a fundamentally different methodology to transform excess rainfall to a runoff hydrograph. The calibration ensured that the rainfall-runoff responses for the model watersheds used in the LTCS were consistent with those that would typically be used to design a pond during development planning.

Pond designs for the third phase of the study are based on a target storage volume as opposed to criteria related to a design storm event. However, it is still beneficial for the SWMM watershed rainfall-runoff response to be comparable to that of the TR-20 model because the TR-20 rainfall-runoff modeling methodology is more likely to be used in land development hydrologic studies.

The previous calibration work utilized the 2- and 100-year COA 3-hour design storm events with 100-acre watersheds having 5% (considered the pre-development condition), 20%, 50%, and 75% impervious cover. Recently, the COA implemented the NRCS Type III 24-hour design storm in place of the 3-hour design storm. In order to be consistent with current City criteria, the SWMM model was recalibrated to TR-20 results for the 2- and 100-year 24-hour design storms.

Calibration was performed for the 100-acre hypothetical watersheds having 5%, 20%, 50%, 75% and 100% impervious cover. The 100% impervious cover watershed was not included in the previous work, but was added for the third phase in order to ensure that the higher end of impervious cover conditions were represented. The TR-20 model parameters summarized in Table 3-1 representing the 5%, 20%, 50%, 75%, and 100% impervious cover watersheds were utilized to generate TR-20 hydrographs. The SWMM model parameters were adjusted in the calibration process to obtain hydrographs that were consistent with the TR-20 hydrographs in runoff volume, peak discharge, and shape.

3.3.2 Calibrated SWMM Model Watershed Parameters

The calibrated SWMM watershed parameter values used with the 3-hour design storms in the previous study phases and 24-hour design storms in the third phase are summarized in Table 3-4. The Manning roughness coefficients, depth of depression storage, percent of impervious cover with no depression storage, percent of runoff routed between subareas, and Horton infiltration decay constant and drying time values were used with the 3-hour storms in the previous work and were not changed for the third phase. The average surface slope value is representative of comparable drainage areas in the upper third of Walnut Creek and was selected in the previous work. Only the overland flow width and Horton minimum and maximum infiltration rates were varied from the values used in the previous work to obtain calibration to the TR-20 model for the 24-hour design storm events.

The overland flow width parameter represents the effective width of sheet flow as it runs toward the receiving channel. For example, a completely paved parking lot sloping toward a gutter on one side of the lot would theoretically have a width of flow equal to the length of the gutter. If a gutter bisected the parking lot with flow entering from both sides, the theoretical width of flow would equal twice the gutter length. However, for natural watersheds, the width of overland flow is much less absolute. Heterogeneous conditions including varying slopes and flow paths may result in a width of overland flow estimate that is variable and basin-specific, and its correlation to physical characteristics of the watershed is difficult to identify. In addition, this is a parameter that will change significantly between pre-development and post-development conditions. Lastly, the SWMM hydrograph peak discharges are sensitive to the overland flow width parameter. Because of the ambiguity regarding its physical relationship to natural watersheds, the overland flow width was treated as a calibration parameter and was adjusted to aid in matching hydrograph peak discharges.

Table 3-4 shows that the calibrated Horton minimum infiltration rate varied significantly for the 3-hour and 24-hour design storm events. The minimum infiltration rate is the rate that will be asymptotically approached as the storm duration increases. Thus, its effect on runoff volume becomes more important with storms of greater duration. The calibrated 3-hour storm value did not produce sufficient runoff volume to be consistent with the TR-20 results when applied in SWMM for the 24-hour storm. Reducing the minimum infiltration rate to the value listed in Table 3-4 achieved more consistent results. The calibrated value agrees with literature values for Hydrologic Group C soils, which were assumed when selecting the TR-20 curve numbers for the hypothetical watershed.[6]

Table 3-4.
Calibrated SWMM Model Watershed Parameters

Parameter	*Value Used with 3-Hour Design Storm*	*Value Used with 24-Hour Design Storm*
Overland Flow Width, 5% Impervious Cover Watershed (ft)	**2500**	**2850**
Overland Flow Width, 20% Impervious Cover Watershed (ft)	**1750**	**3175**
Overland Flow Width, 50% Impervious Cover Watershed (ft)	**750**	**1275**
Overland Flow Width, 75% Impervious Cover Watershed (ft)	**750**	**1000**
Overland Flow Width, 100% Impervious Cover Watershed (ft)	**NA**	**2100**
Average Surface Slope (Percent)	1.5	1.5
Manning n for Impervious Cover	0.014	0.014
Manning n for Pervious Cover	0.15	0.15
Depth of Depression Storage on Impervious Areas (in)	0.03	0.03
Depth of Depression Storage on Pervious Areas (in)	0.2	0.2
Percent of Impervious Area with No Depression Storage	50	50
Percent of Runoff Routed Between Sub-areas	100	100
Horton Infiltration Parameters		
Maximum Infiltration Rate (in/hr)	**2.0**	**1.5**
Minimum Infiltration Rate (in/hr)	**0.5**	**0.15**
Decay Constant (1/hr)	5	5
Drying Time (days)	2	2

[6] Musgrave, G.W., "How Much Water Enters the Soils," U.S.D.A. Yearbook, U.S. Department of Agriculture, Washington, DC, 1955, pp. 151-159, cited in XPSWMM User's Manual accessed online at http://www.xpsoftware.com.au/products/swmm/webhelp/xpswmm.htm, January 8, 2009.

The LTCS modeling was conducted for contributing watersheds having 5%, 10%, 20%, 30%, 40%, 50%, 60%, 75%, 85%, 95%, and 100% impervious cover, and therefore watershed parameters were required for each of these contributing watershed impervious cover levels. The only parameters that were varied between the different watersheds were the percent impervious cover and the overland flow width. The overland flow widths calibrated to the 24-hour storm for the 5%, 20%, 50%, 75%, and 100% impervious cover watersheds listed in Table 3-4 were used to estimate values for the 10%, 30%, 40%, 60%, 85%, and 95% impervious cover watersheds. The overland flow width values for all watersheds are summarized in Table 3-5.

Table 3-5.
Summary of Overland Flow Width Values

Watershed Percent Impervious Cover	*Overland Flow Width (ft)*
5	2850 [1]
10	2960 [2]
20	3175 [1]
30	2335 [2]
40	1690 [2]
50	1275 [1]
60	1010 [2]
75	1000 [1]
85	1300 [2]
95	1775 [2]
100	2100 [1]

[1]Calibrated value
[2]Estimated value based on calibrated values.

3.3.3 Comparison of SWMM and TR-20 Hydrographs

The peak discharge and runoff volume from the calibrated SWMM model for the 2- and 100-year 24-hour storm events falling on the 5%, 20%, 50%, 75% and 100% impervious cover watersheds are compared to the peak discharge and runoff volume computed with TR-20 in Tables 3-6 and 3-7. Table 3-6 shows that the calibrated SWMM model underestimates TR-20 2-year peak discharges and overestimates 100-year peak discharges throughout the range of impervious cover levels. For a given impervious cover level, the percentage difference between

SWMM and TR-20 peak discharges for the 2-year and 100-year events is similar, indicating that attempting to adjust parameters to achieve a better match for one event would be successful only at the expense of creating additional error for the other event. Table 3-7 shows that SWMM tends to match the 100-year TR-20 runoff volumes better than the 2-year runoff volumes, with the 2-year differences being greatest for the 50% and 75% impervious cover watersheds. The variation with impervious cover and magnitude of the volume differences are similar to those that were observed in the 3-hour storm calibration during the previous work.

Table 3-6.
Comparison of TR-20 and SWMM 24-Hour Storm Simulation Results – Peak Discharge

	5% IC Peak Discharge (cfs)		20% IC Peak Discharge (cfs)		50% IC Peak Discharge (cfs)		75% IC Peak Discharge (cfs)		100% IC Peak Discharge (cfs)	
Model	**2-Yr**	**100-Yr**	**2-Yr**	**100-Yr**	**2-Yr**	**100-Yr**	**2-Yr**	**100-Yr**	**2-Yr**	**100-Yr**
TR-20	58.4	351.0	98.3	485.6	133.5	527.4	164.9	553.1	233.1	699.3
SWMM	55.9	366.9	97.7	490.3	128.9	545.7	149.1	610.8	212.6	762.8
% Difference[1]	-4.4	4.5	-0.6	1.0	-3.5	3.5	-9.6	10.4	-8.8	9.1

[1]% Difference = 100 x (SWMM Result - TR-20 Result) / TR-20 Result

Table 3-7.
Comparison of TR-20 and SWMM 24-Hour Storm Simulation Results – Total Runoff Volume

	5% IC Runoff Volume (acft)		20% IC Runoff Volume (acft)		50% IC Runoff Volume (acft)		75% IC Runoff Volume (acft)		100% IC Runoff Volume (acft)	
Model	**2-Yr**	**100-Yr**	**2-Yr**	**100-Yr**	**2-Yr**	**100-Yr**	**2-Yr**	**100-Yr**	**2-Yr**	**100-Yr**
TR-20	10.0	57.8	12.7	63.2	17.0	70.6	21.5	76.8	26.7	82.9
SWMM	10.1	56.3	13.4	61.1	18.7	69.8	23.8	77.5	28.6	84.9
% Difference[1]	1.0	-2.5	5.5	-3.3	10.0	-1.2	10.7	0.8	7.1	2.4

[1]% Difference = 100 x (SWMM Result - TR-20 Result) / TR-20 Result

Figures 3-1 and 3-2 simultaneously plot the resulting SWMM and TR-20 hydrographs for the 2-year storm on the 5% impervious cover watershed and the 100-year storm on the 100% impervious cover watershed. The plots show that the shapes of the hydrographs produced by the two models are generally consistent.

Table 3-8 provides a comparison of the design storm peak discharges and runoff volumes computed with the 3-hour calibration of the previous study phases and the 24-hour calibration of the third phase. The 100% impervious cover watershed was not run in the previous work and therefore is not included in Tables 3-8. The information in Table 3-8 allows a direct comparison of the effects of the difference in the two calibrations. The data show that the 24-hour calibration produces greater total runoff and higher peak discharges than the 3-hour calibration for a given storm event. This is consistent with the decreased infiltration associated with the 24-hour storm calibration.

The data in Table 3-8 also show that the percent increase in peak discharge and total runoff volume associated with the 24-hour calibration decreases with increased impervious cover. For example, the percent increase in total runoff volume for the 2-year 3-hour storm with the 5 % impervious cover watershed is 96%, while it is only 10% for same storm with the 75% impervious cover watershed. The difference in the two calibrations is less prominent at higher impervious cover levels than at lower impervious cover levels. This is consistent with the infiltration parameters only affecting the pervious portion of the watershed; changing these parameters has less of an effect on watersheds with less pervious cover.

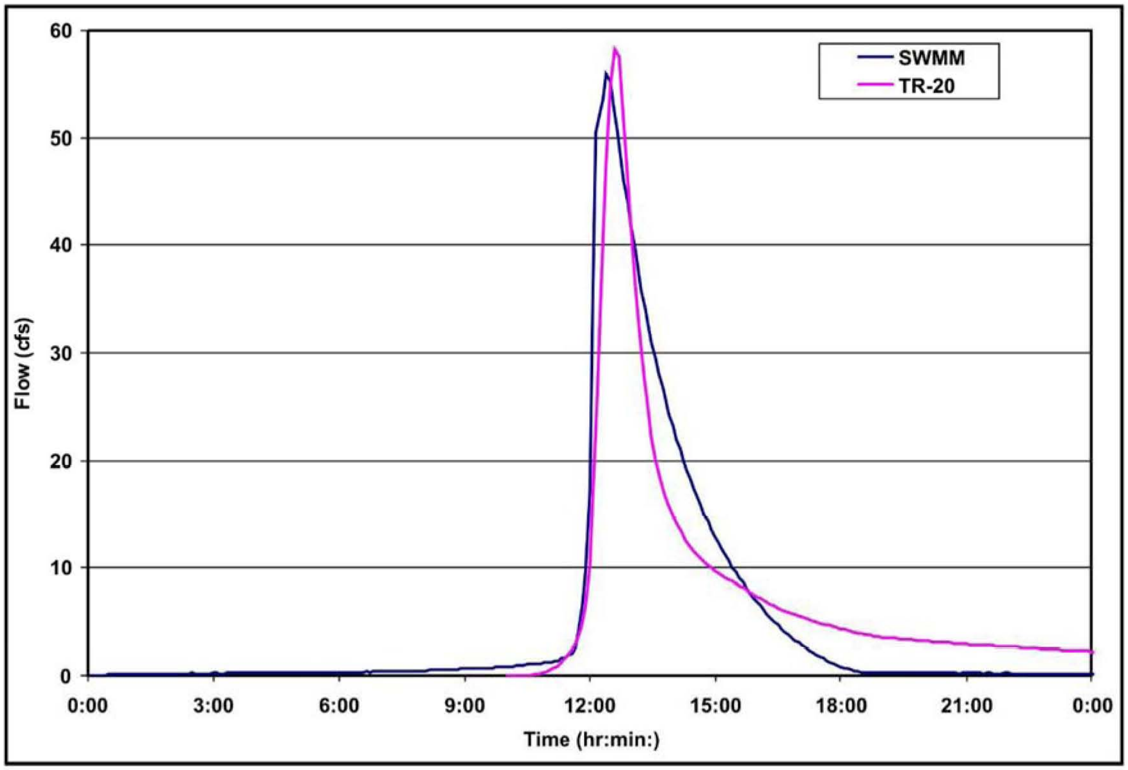

Figure 3-1. SWMM vs. TR-20 5% Impervious Cover Watershed Runoff 2-Year, 24-Hour Storm

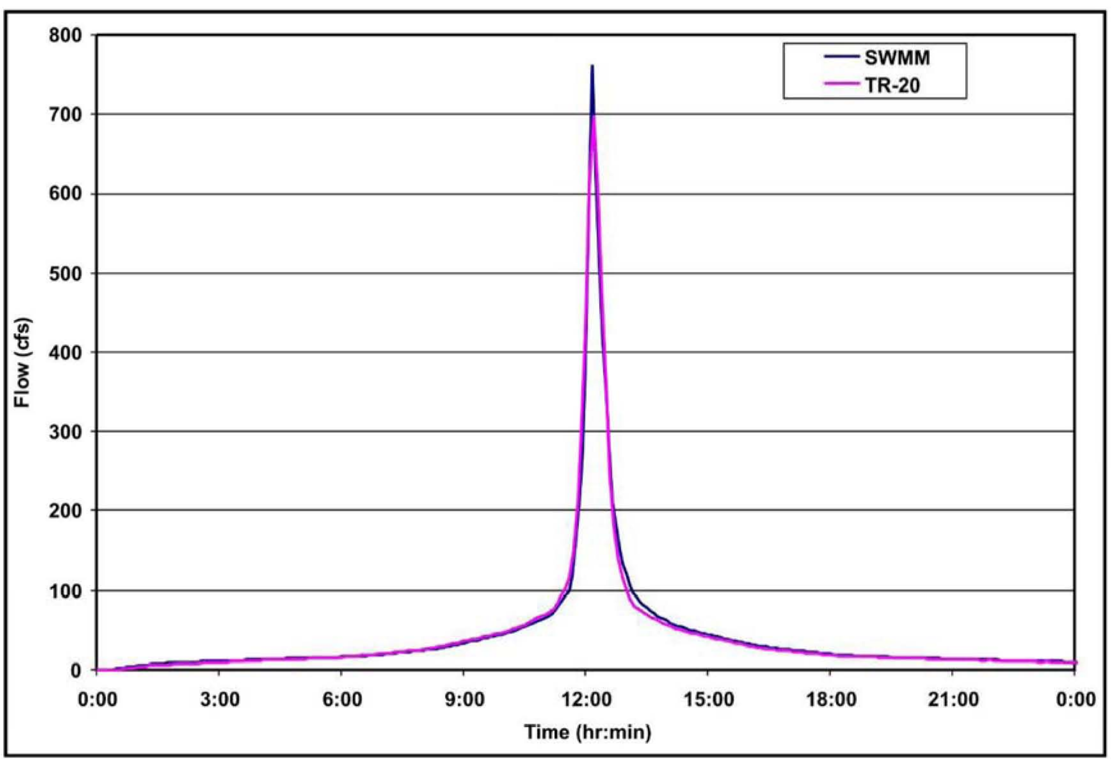

Figure 3-2. SWMM vs. TR-20 100% Impervious Cover Watershed Runoff 100-Year, 24-Hour Storm

Table 3-8.
Design Storm Simulation Results

Watershed Impervious Cover	SWMM Simulation	Peak Dis-charge (cfs)	Total Runoff Volume (acft)	Increase in Peak Discharge for 24-Hr Calibration Compared to 3-Hr Calibration (%)	Increase in Volume for 24-Hr Calibration Compared to 3-Hr Calibration (%)
5%	2-Yr 3-Hr Storm with 3-Hr Calibration	63.6	5.9		
5%	2-Yr 3-Hr Storm with 24-Hr Calibration	93.3	11.5	47	96
5%	2-Yr 24-Hr Storm with 3-Hr Calibration	27.6	3.3		
5%	2-Yr 24-Hr Storm with 24-Hr Calibration	55.9	10.1	102	209
5%	100-Yr 3-Hr Storm with 3-Hr Calibration	315.1	34.1		
5%	100-Yr 3-Hr Storm with 24-Hr Calibration	394.0	44.9	25	31
5%	100-Yr 24-Hr Storm with 3-Hr Calibration	257.7	33.0		
5%	100-Yr 24-Hr Storm with 24-Hr Calibration	366.9	56.3	42	71
50%	2-Yr 3-Hr Storm with 3-Hr Calibration	185.1	12.5		
50%	2-Yr 3-Hr Storm with 24-Hr Calibration	234.3	16.0	27	28
50%	2-Yr 24-Hr Storm with 3-Hr Calibration	98.2	14.9		
50%	2-Yr 24-Hr Storm with 24-Hr Calibration	128.9	18.7	31	25
50%	100-Yr 3-Hr Storm with 3-Hr Calibration	493.1	43.0		
50%	100-Yr 3-Hr Storm with 24-Hr Calibration	600.6	50.1	22	17
50%	100-Yr 24-Hr Storm with 3-Hr Calibration	419.0	56.4		
50%	100-Yr 24-Hr Storm with 24-Hr Calibration	545.7	69.8	30	24
75%	2-Yr 3-Hr Storm with 3-Hr Calibration	228.6	17.1		
75%	2-Yr 3-Hr Storm with 24-Hr Calibration	270.0	18.8	18	10
75%	2-Yr 24-Hr Storm with 3-Hr Calibration	128.0	21.9		
75%	2-Yr 24-Hr Storm with 24-Hr Calibration	149.1	23.8	17	9
75%	100-Yr 3-Hr Storm with 3-Hr Calibration	628.5	50.6		
75%	100-Yr 3-Hr Storm with 24-Hr Calibration	703.3	53.6	12	6
75%	100-Yr 24-Hr Storm with 3-Hr Calibration	529.2	71.4		
75%	100-Yr 24-Hr Storm with 24-Hr Calibration	610.8	77.5	15	9

Note: All design storm simulations summarized in Table 3-8 were conducted with SWMM Version 5.0.013.

3.4 Computation of Erosion Indices

The ESP erosion index value for each of the 48 ponds was computed based on the LTCS results. The pond discharge hydrographs for the 15-year (1990 – 2004) simulation period, with the pond discharge tabulated at 15-minute intervals, were input to a FORTRAN program that computed the ESP values. The ESP index value is defined by the following equation:

$$ESP = \sum_{t=0}^{t=15\,yrs} (\tau_t - \tau_c) \cdot V_t \text{ for all } \tau_t \succ \tau_c \quad [\text{lb/ft/sec}] \tag{3}$$

Where:

τ_t is the channel shear stress at time t (lb/ft^2);

τ_c is the critical shear stress mobilizing the channel bed material (lb/ft^2) = 0.24 lb/ft^2 for medium gravel; and

V_t is the channel average velocity at time t (ft/sec).

The 2-year receiving channel discharge-velocity-shear-depth rating curve developed during the previous work provided the receiving channel characteristics the FORTRAN code required to compute the ESP value from the pond discharge values. The ESP values computed for each of the 48 ponds plus the 5% impervious cover watershed without a pond are listed in Table 3-9.

Table 3-9.
Pond ESP Values
(page 1 of 2)

Pond ID	Pond Volume (acft)	ESP (lb/ft/s)	Pond ID	Pond Volume (acft)	ESP (lb/ft/s)
5% IC (Undeveloped Watershed Without Pond)	NA	806			
			60% Impervious Cover Watershed		
10% Impervious Cover Watershed			60% IC 60% Vol	5.39	930
10% IC 70% Vol	0.53	863	60% IC 70% Vol	6.29	780
10% IC 85% Vol	0.64	837	60% IC 85% Vol	7.64	606
10% IC 95% Vol	0.72	821	60% IC 95% Vol	8.54	517
10% IC 115% Vol	0.87	789	60% IC 115% Vol	10.33	394
20% Impervious Cover Watershed			**75% Impervious Cover Watershed**		
20% IC 70% Vol	1.59	874	75% IC 60% Vol	7.51	877
20% IC 85% Vol	1.93	819	75% IC 70% Vol	8.76	704
20% IC 95% Vol	2.16	778	75% IC 85% Vol	10.64	515
20% IC 115% Vol	2.62	706	75% IC 95% Vol	11.89	431
			75% IC 115% Vol	14.40	315
30% Impervious Cover Watershed			**85% Impervious Cover Watershed**		
30% IC 70% Vol	2.61	868	85% IC 50% Vol	7.44	1,099
30% IC 85% Vol	3.17	772	85% IC 60% Vol	8.93	855
30% IC 95% Vol	3.54	715	85% IC 70% Vol	10.41	668
30% IC 115% Vol	4.29	618	85% IC 85% Vol	12.65	481
			85% IC 95% Vol	14.13	402
			85% IC 115% Vol	17.11	287
40% Impervious Cover Watershed			**95% Impervious Cover Watershed**		
40% IC 70% Vol	3.62	862	95% IC 50% Vol	8.62	1,097
40% IC 85% Vol	4.40	739	95% IC 60% Vol	10.34	827
40% IC 95% Vol	4.92	662	95% IC 70% Vol	12.06	633
40% IC 115% Vol	5.95	544	95% IC 85% Vol	14.65	451
			95% IC 95% Vol	16.37	368
			95% IC 115% Vol	19.82	318

Table 3-9.
Pond ESP Values
(page 2 of 2)

Pond ID	*Pond Volume (acft)*	*ESP (lb/ft/s)*	*Pond ID*	*Pond Volume (acft)*	*ESP (lb/ft/s)*
50% Impervious Cover Watershed			**100% Impervious Cover Watershed**		
50% IC 70% Vol	4.64	873	100% IC 50% Vol	9.21	1,091
50% IC 85% Vol	5.63	710	100% IC 60% Vol	11.05	813
50% IC 95% Vol	6.30	631	100% IC 70% Vol	12.89	618
50% IC 115% Vol	7.62	490	100% IC 85% Vol	15.65	438
			100% IC 95% Vol	17.49	361
			100% IC 115% Vol	21.18	347

Section 4
Stream Protection Curve

4.1 Curve Development

The ESP values computed from the LTCS pond outflow hydrographs (Table 3-9) were used to develop the final stream protection curve. For each of the 10 watershed impervious cover levels, the pond volume that would produce an ESP value equal to that of the undeveloped 5% impervious cover watershed (i.e., the stream protection volume) was estimated by linear interpolation.

Figures 4-1 through 4-10 show ESP as a function of pond volume for each of the watersheds. The ESP of the undeveloped, uncontrolled watershed is also plotted on each chart. The figures show that linear interpolation provides a reasonable estimate of the stream protection volume. The approximate slope of the curve at the stream protection volume is noted on each of the figures. Overall, the magnitude of the slope decreases with increased watershed impervious cover. A lower slope magnitude indicates that changing the pond volume has less of an effect on the ESP. Thus, reducing the ESP by a given amount takes more volume at greater levels of impervious cover than at lesser, as would be expected.

Figure 4-11 shows the interpolated stream protection volumes plotted as a function of impervious cover and is the final stream protection curve. The pond volume at 5% impervious cover is by definition zero because the 5% impervious cover watershed is considered the undeveloped condition.

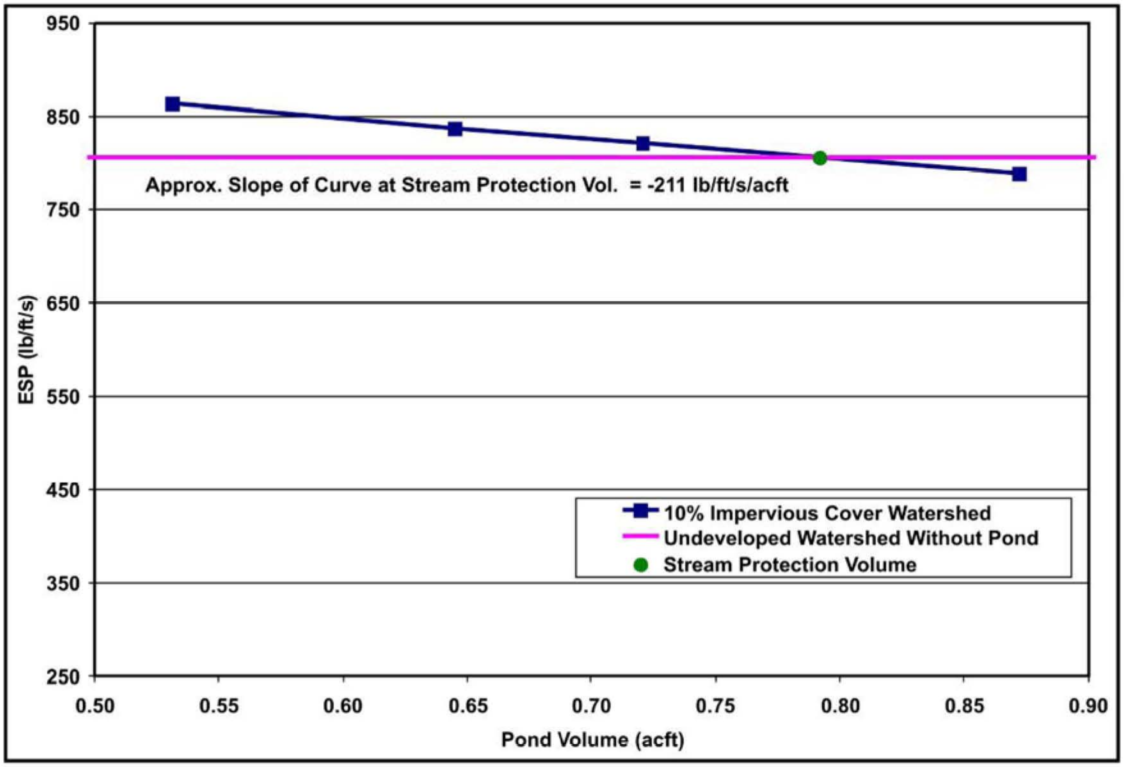

Figure 4-1. ESP as a Function of Pond Volume, 10% Impervious Cover Watershed

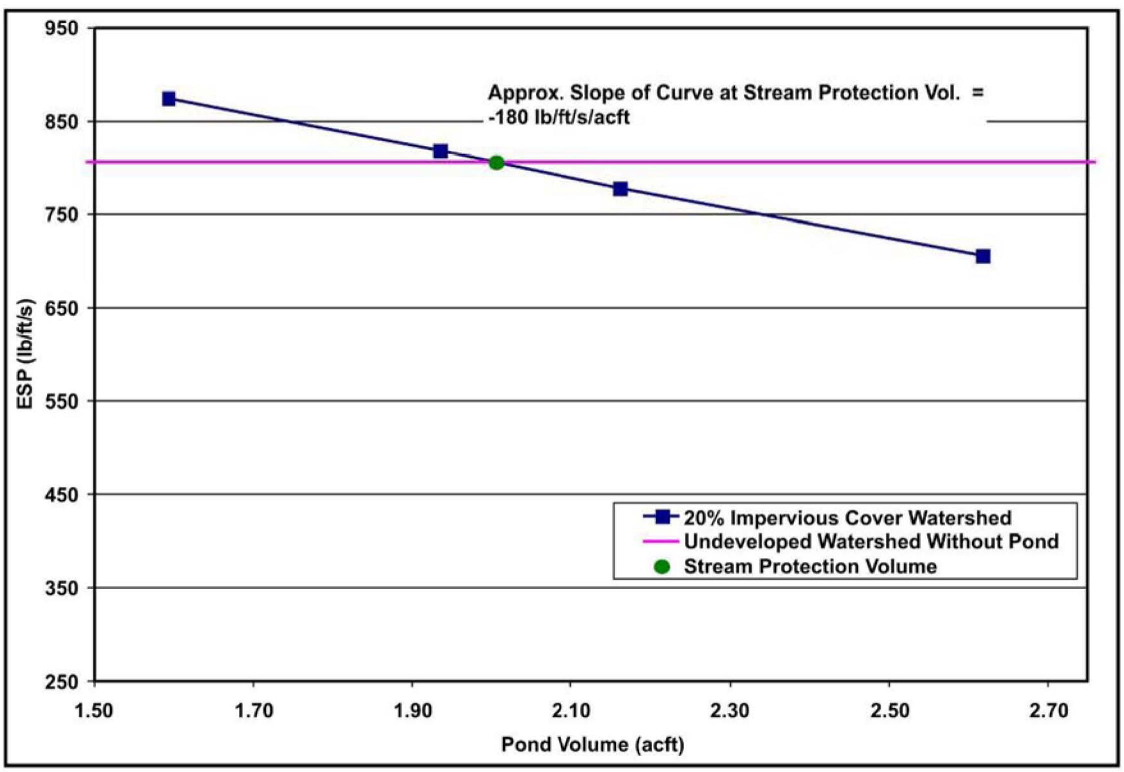

Figure 4-2. ESP as a Function of Pond Volume, 20% Impervious Cover Watershed

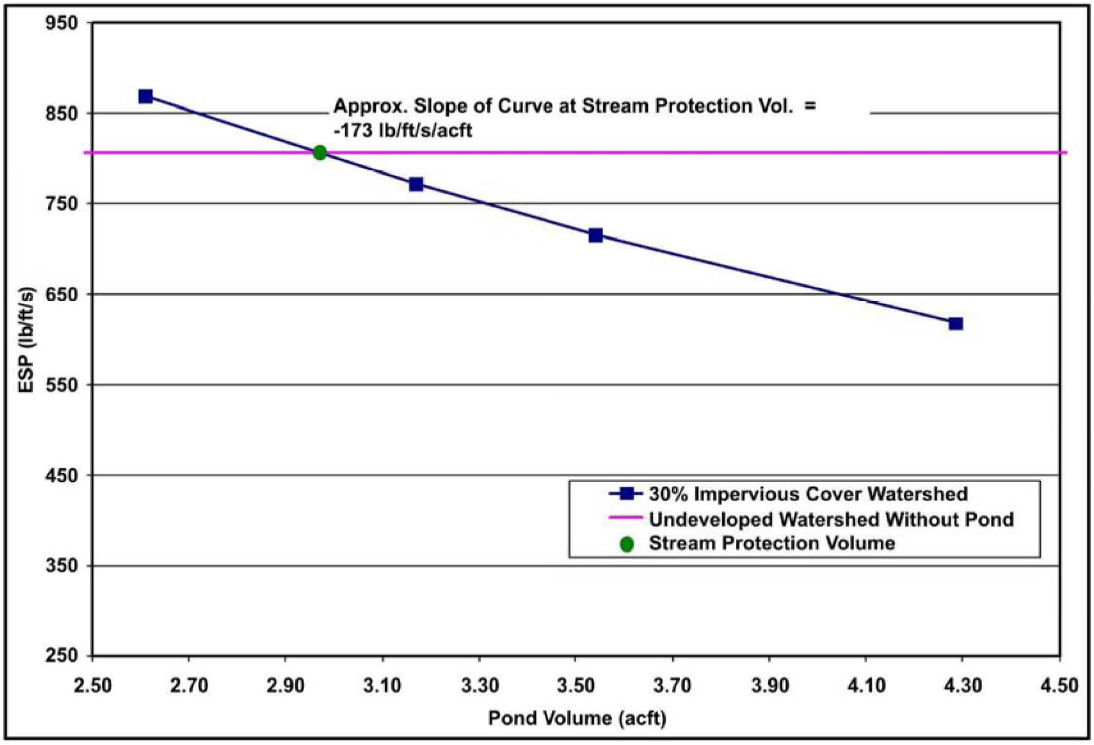

Figure 4-3. ESP as a Function of Pond Volume, 30% Impervious Cover Watershed

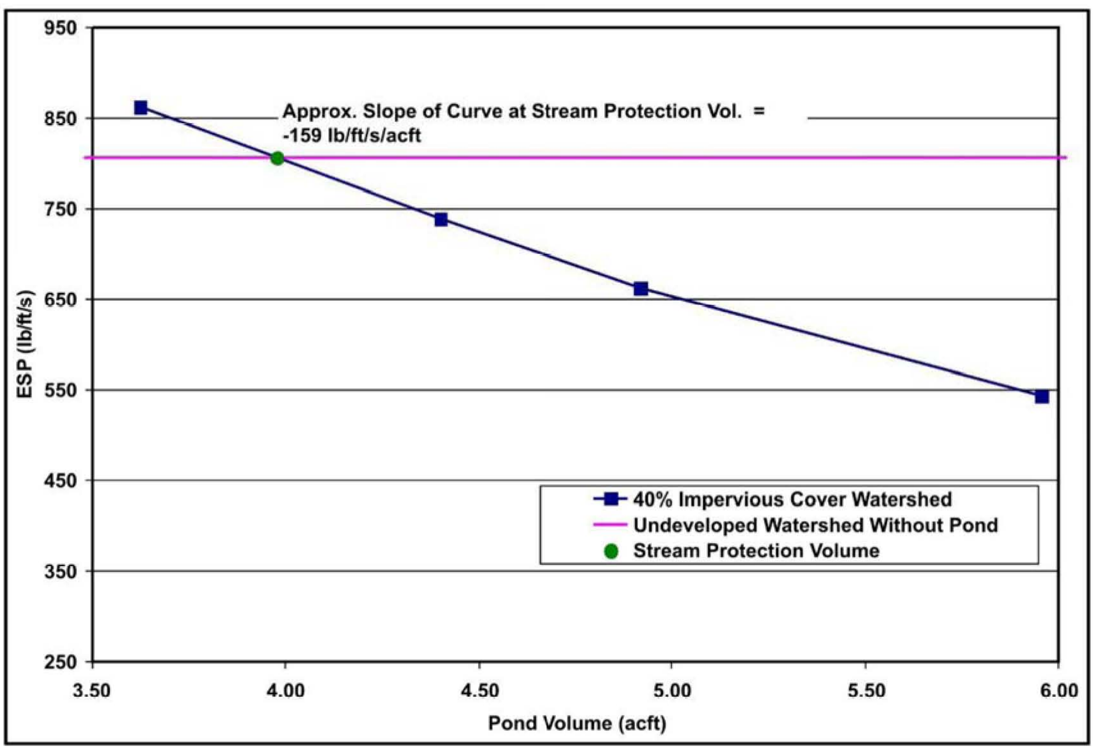

Figure 4-4. ESP as a Function of Pond Volume, 40% Impervious Cover Watershed

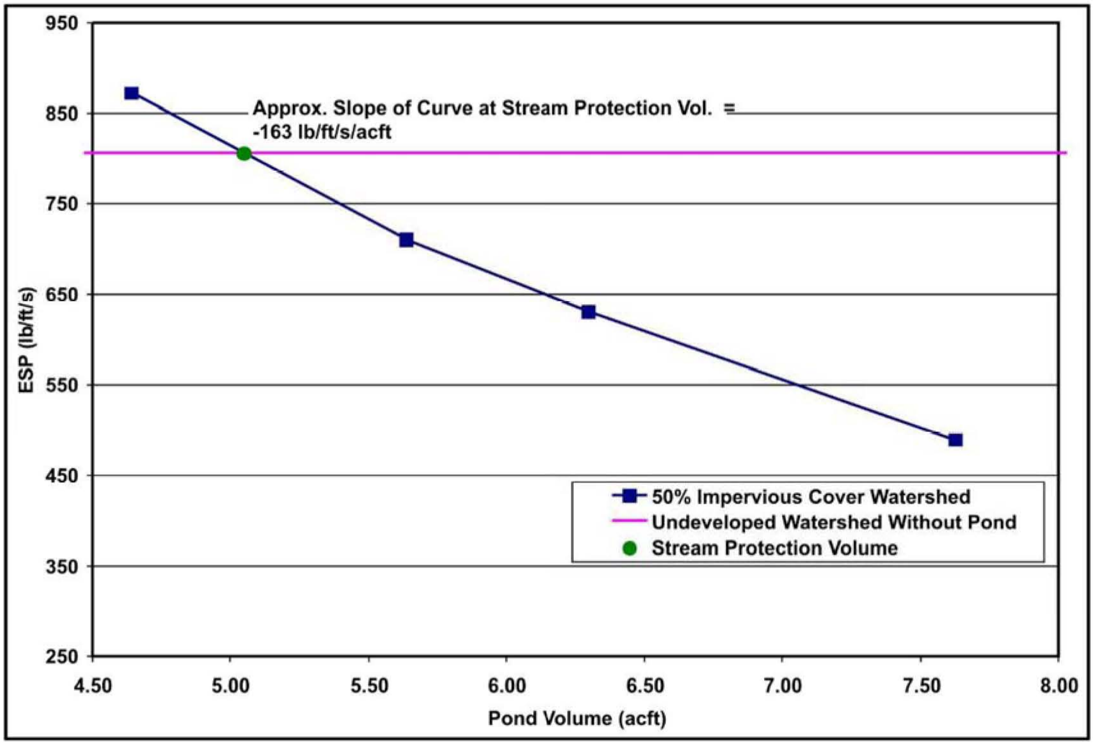

Figure 4-5. ESP as a Function of Pond Volume, 50% Impervious Cover Watershed

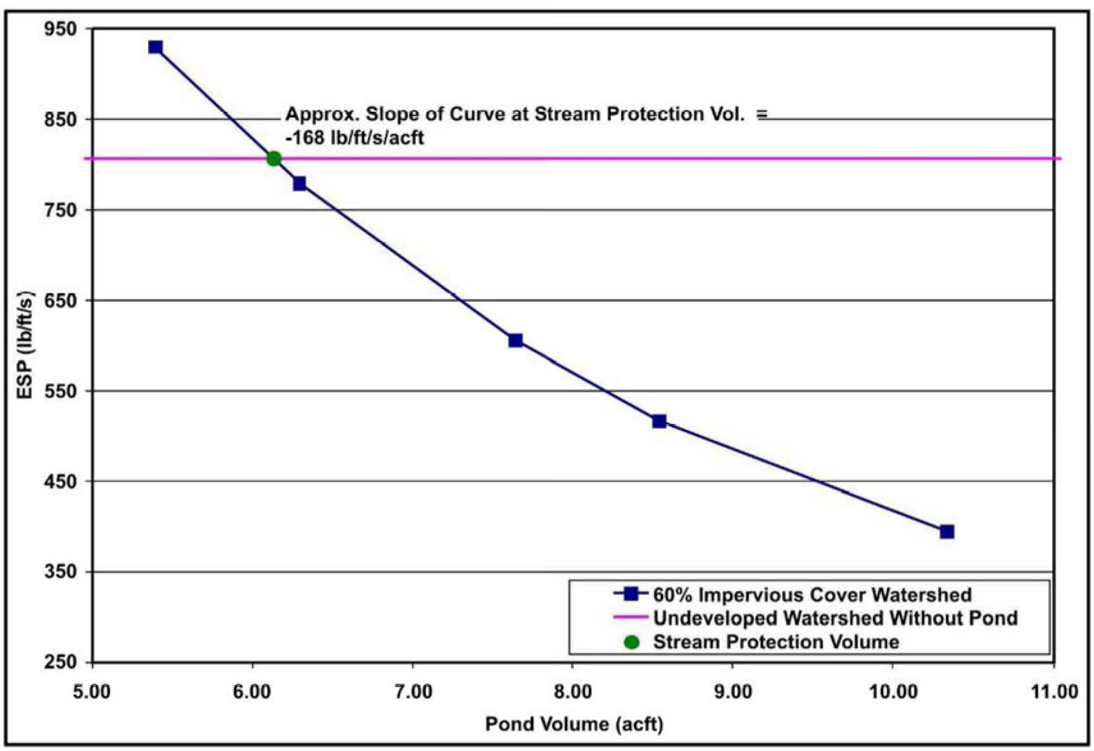

Figure 4-6. ESP as a Function of Pond Volume, 60% Impervious Cover Watershed

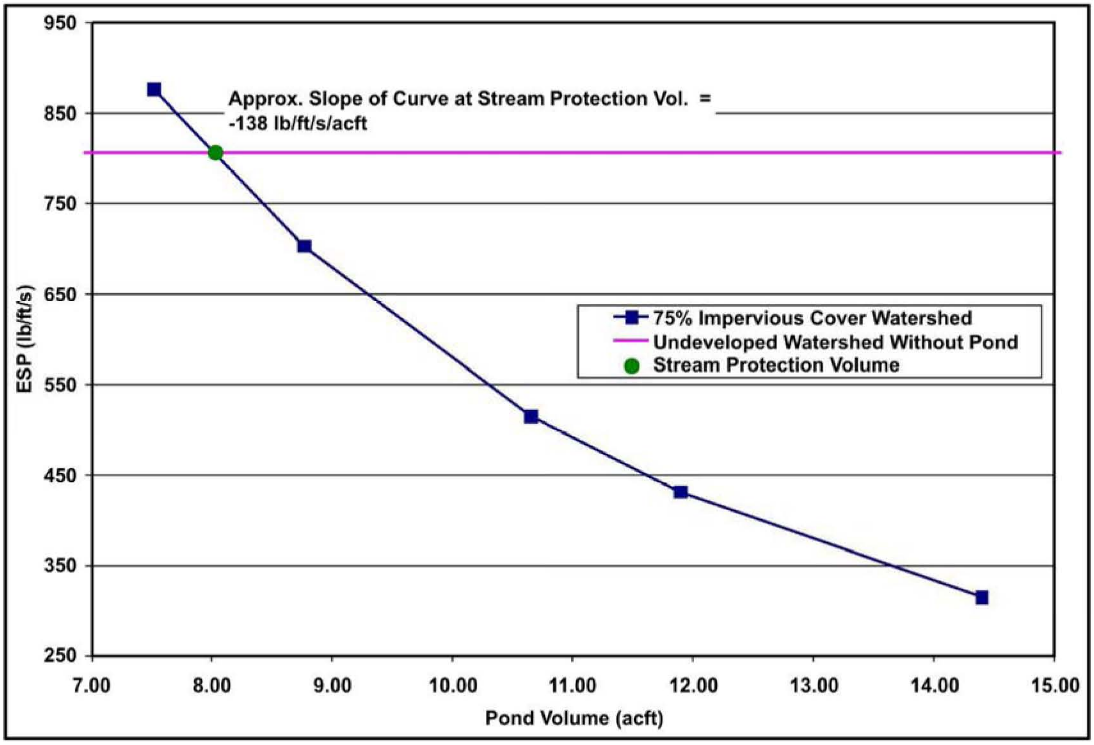

Figure 4-7. ESP as a Function of Pond Volume, 75% Impervious Cover Watershed

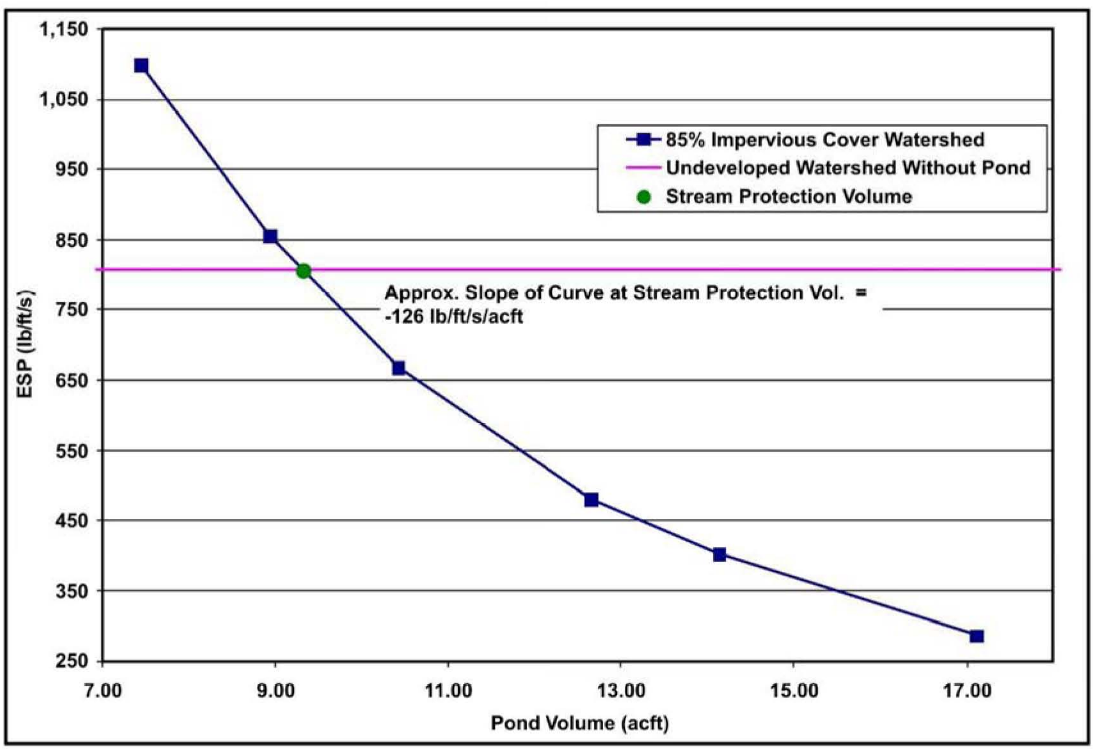

Figure 4-8. ESP as a Function of Pond Volume, 85% Impervious Cover Watershed

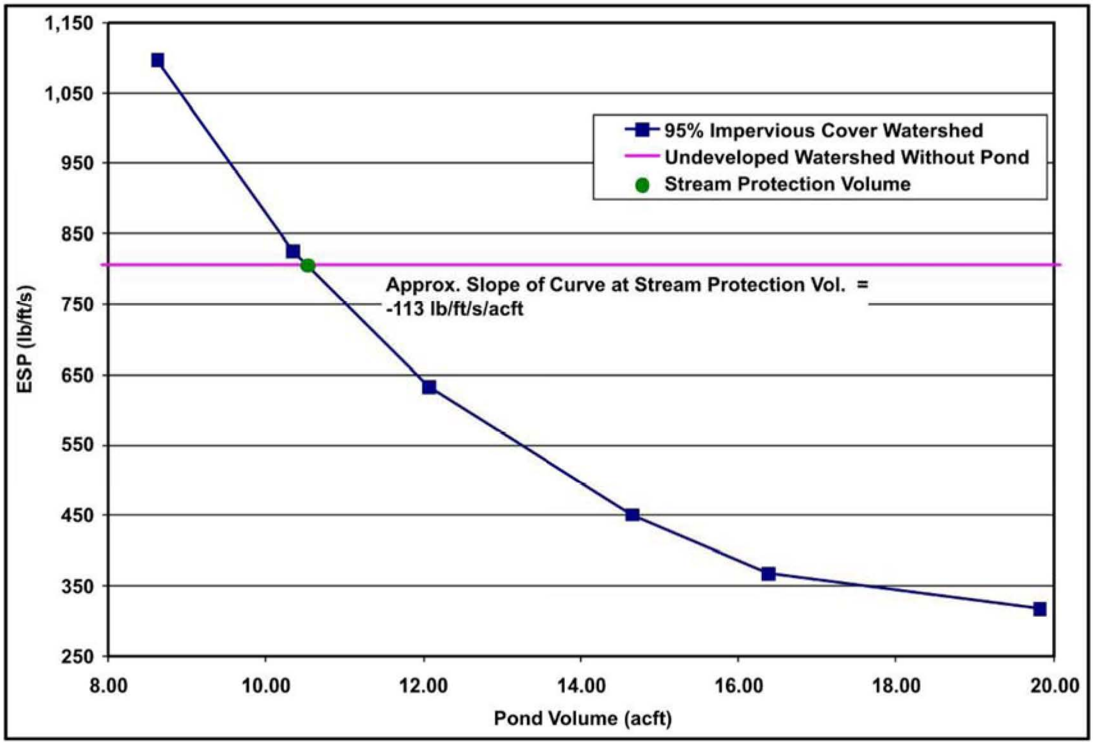

Figure 4-9. ESP as a Function of Pond Volume, 95% Impervious Cover Watershed

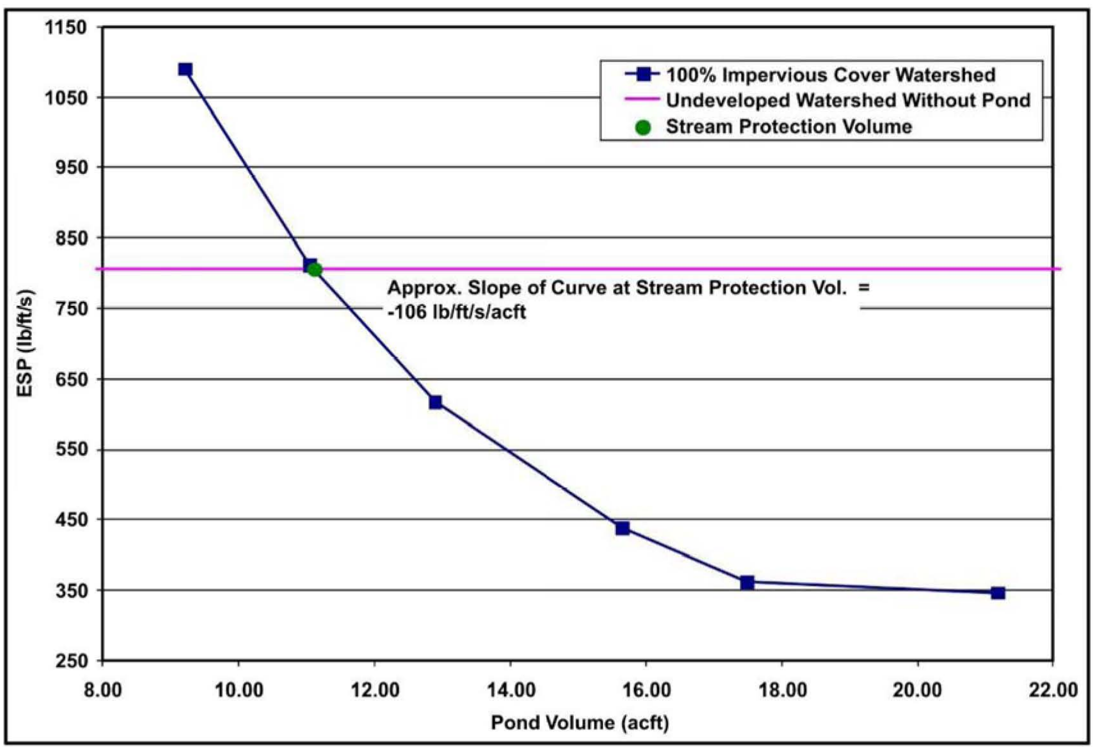

Figure 4-10. ESP as a Function of Pond Volume, 100% Impervious Cover Watershed

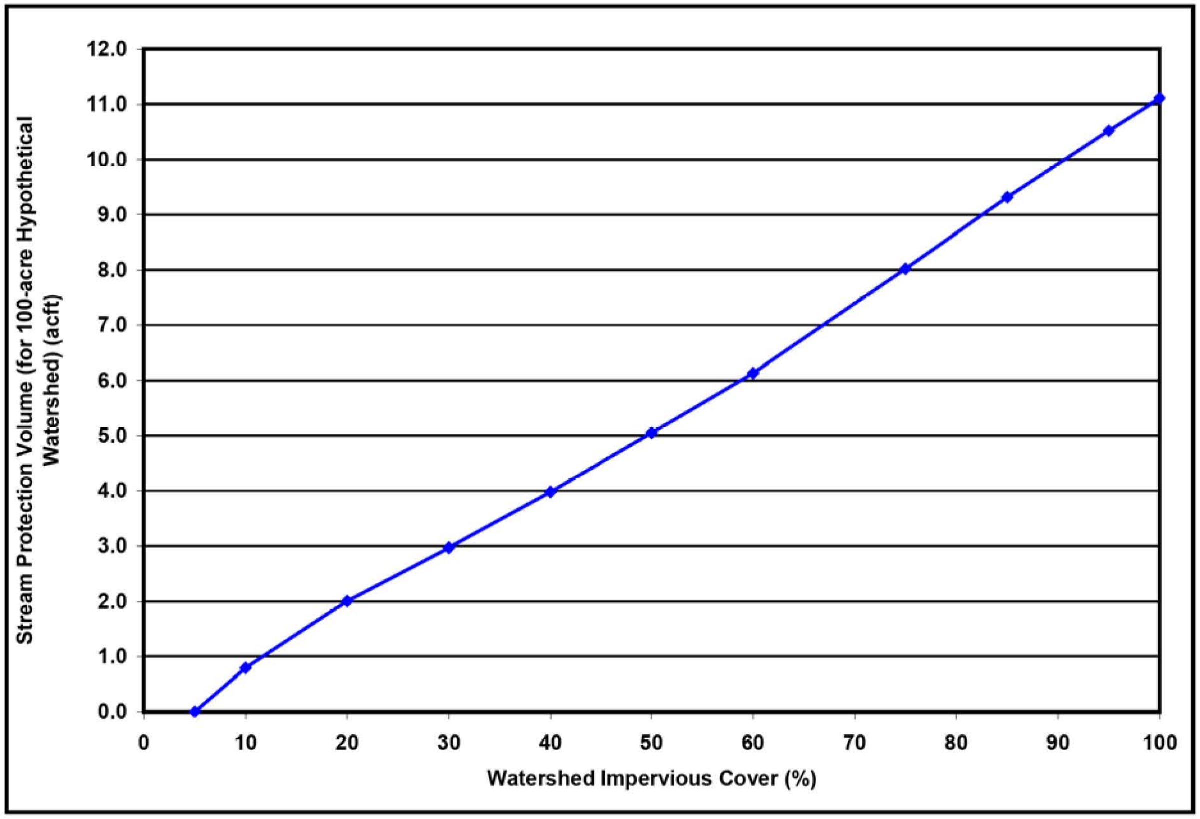

Figure 4-11. Stream Protection Curve for 100-acre Developing Watershed

4.2 Limitations

The stream protection curve shown in Figure 4-11 was developed based on assumptions regarding the watershed characteristics, receiving channel characteristics, rainfall event, and pond design. Watershed characteristics that may have significant impact on the curve include the watershed area, soil infiltration properties, and time of concentration. Important receiving channel characteristics include channel cross section, bed material, and slope. The rainfall duration and temporal distribution also influence the curve. In addition, ponds with the same volume but different shape and depth could be expected to produce different ESP results. The receiving channel characteristics of bank full capacity and bed material have been considered in the previous phases of the study. The results of the third phase compared to previous work provide insight on the effect of storm duration. However, the sensitivity of the curve to other significant variables has not been quantified. Therefore, generalizing the curve for use in situations that do not conform to the assumptions used in its development may not produce reliable estimates of the required stream protection volume.

4.3 Comparison of Curve to City of Austin Water Quality Volume

Figure 4-12 shows the stream protection curve with the pond volume expressed on a unit basis. The curve is provided in tabular form in Table 4-1. The values plotted in Figure 4-12 and listed in Table 4-1 were obtained by dividing the stream protection volumes used to generate Figure 4-11 by the area of the hypothetical watershed (100 acres). The COA 1/2 inch plus 1/10th inch standard water quality volume is also plotted in Figure 4-12 and listed in Table 4-1. Comparing the two curves suggests that the COA standard volume provides more storage than is necessary to match predevelopment erosion potential as quantified by ESP for all but the highest levels of impervious cover (above approximately 92%).

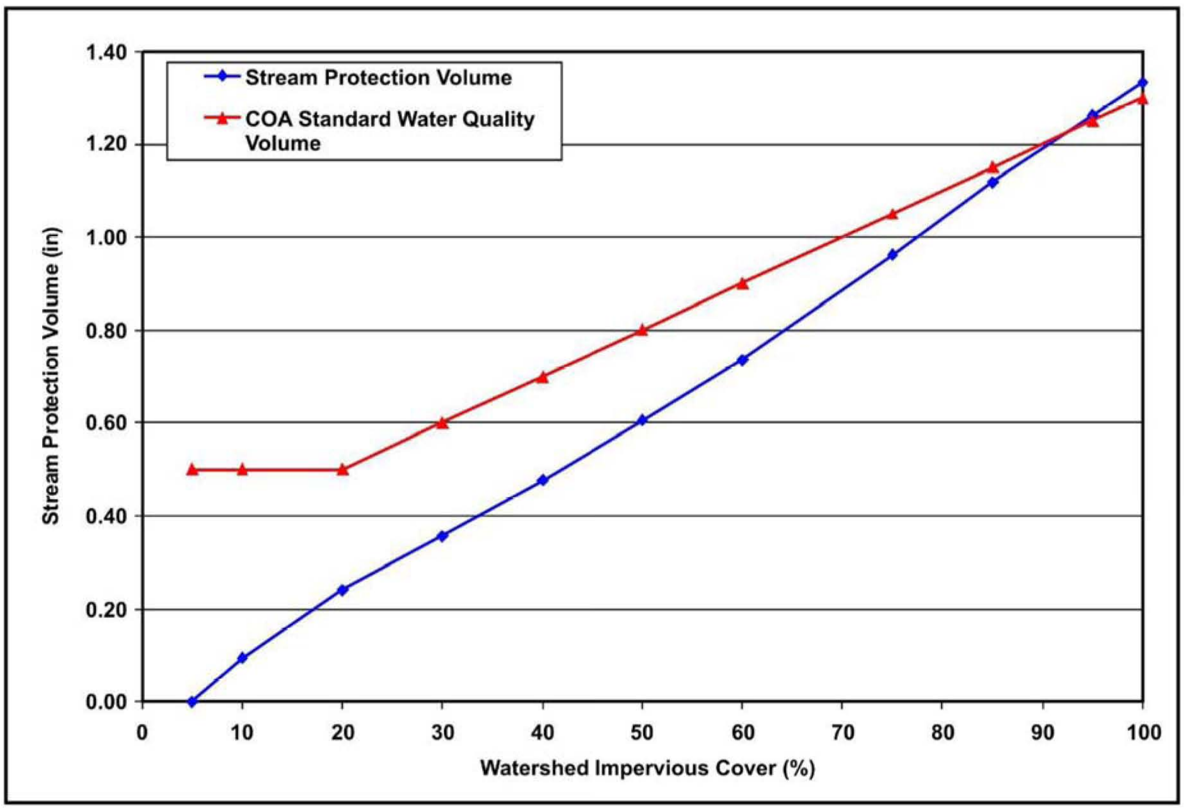

Figure 4-12. Stream Protection Curve Compared to COA Water Quality Volume

Table 4-1.
Stream Protection Volume and COA Water Quality Volume

Watershed IC (%)	Stream Protection Volume (in)	COA Standard Water Quality Volume (in)
5	0.00	0.50
10	0.10	0.50
20	0.24	0.50
30	0.36	0.60
40	0.48	0.70
50	0.61	0.80
60	0.74	0.90
75	0.96	1.05
85	1.12	1.15
95	1.26	1.25
100	1.33	1.30

The results of the previous study phases indicated that the COA standard water quality volume may provide more protection than is necessary at impervious cover levels less than approximately 50% and less protection than is necessary at impervious cover levels greater than approximately 50%. In showing that the COA standard volume provides more protection than is necessary over a wider range of impervious cover levels, the results of the current phase differ from those of the previous work. The primary factor in this difference is the replacement of the 3-hour design storm event with the 24-hour event. In recalibrating the SWMM model to the longer event, the resulting watershed response produced higher peak discharges and greater total runoff volumes for both frequent and infrequent rainfall events, as shown by the data provided in Table 3-8.

The ESP values summarized in Table 4-2 show that with higher peak discharges and greater runoff volumes, the erosion potential associated with the uncontrolled watershed is increased for the 24-hour calibration compared to the 3-hour calibration at all impervious cover levels. The last column in Table 4-2 provides the ratio of the 24-hour calibration ESP value to the 3-hour calibration ESP value and shows that the relative difference between the two decreases with increased impervious cover. This is consistent with the impervious cover trends in the design storm peak runoff rate and runoff volume that were identified in Table 3-8.

The third and fifth columns of Table 4-2 list the ratio of the ESP value to that of the undeveloped (5% impervious cover) watershed. For the 3-hour calibration, the 75% impervious cover uncontrolled watershed produces an ESP value over 11 times greater than that of the undeveloped (5% impervious cover) watershed. For the 24-hour calibration, the 75% impervious cover uncontrolled watershed produces an ESP value that is slightly less than 4 times greater than that of the undeveloped watershed. This indicates that, for the 24-hour calibration, detention ponds need to do less to mitigate the watershed runoff erosion potential to predevelopment levels. As a corollary of this, a pond of a given volume would be expected to show better performance in terms of its ability to reduce ESP values to the pre-developed condition when evaluated with the 24-hour calibration than when evaluated with the 3-hour calibration. Additional discussion regarding the effect of the design storm duration on the SWMM model calibration and the resulting differences in the findings of the previous work and current study phase is provided in Appendix B.

Table 4-2.
Uncontrolled Watershed ESP Values

	3-Hr Phase II Calibration		24-Hr Phase III Calibration		
Impervious Cover (IC)	**Uncontrolled Watershed ESP Value**	**Ratio of ESP Value to 5% IC ESP Value**	**Uncontrolled Watershed ESP Value**	**Ratio of ESP Value to 5% IC ESP Value**	**Ratio of 24-Hr Calibration ESP to 3-Hr Calibration ESP**
5%	251	1.0	806	1.0	3.2
20%	776	3.1	1354	1.7	1.7
50%	1811	7.2	2266	2.8	1.3
75%	2865	11.4	3109	3.9	1.1

Note: All LTCS summarized in Table 4-2 were conducted with SWMM Version 5.0.013.

Section 5
Conclusion and Recommendations

The results of the current study phase suggest that the COA standard water quality volume provides more storage than is necessary to match predevelopment erosion potential for all but the highest levels of watershed impervious cover (above approximately 92%). However, this conclusion is arrived at on the basis of assumptions regarding watershed characteristics, receiving channel characteristics, rainfall event, and pond design. Should the City have an interest in pursuing further work on quantifying the long-term benefits of on-site erosion detention, it is recommended that effort be focused on assessing the generalized applicability of the stream protection curve; i.e., whether the curve can be applied to cases that deviate from the specific assumptions upon which its development was based. Additional work in the following areas would be relevant:

- Assess the effect of the pond configuration on the erosion index. The current work assumed a 4-ft pond depth and vertical side slope, and only the pond area was varied to achieve the desired volume. A deeper or shallower pond storing the same volume and releasing over the same drawdown period would be expected to produce a different outflow hydrograph and therefore different ESP results. For example, a deep pond with less area may produce higher peak discharges.
- Assess the effect of the watershed area on the erosion index. The current work assumed a 100-acre watershed area. Evaluating smaller and larger areas would provide insight to the scalability of the stream protection curve.
- Assess the effect of the receiving channel cross section geometry. For example, wider and shallower receiving channels designed to carry the same peak discharge may produce different ESP results.

The work conducted to date has demonstrated the methodology, and additional insight could be gained by continuing to apply this methodology to examine the factors listed above as well as the effect of other variables.

Appendix A

Pond Stage-Storage-Discharge Tables

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **10% IC 70% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	0.13	0.00	0.0
496.5	0.13	0.07	0.1
497.0	0.13	0.13	0.1
497.5	0.13	0.20	0.1
498.0	0.13	0.27	0.1
498.5	0.13	0.33	0.2
499.0	0.13	0.40	0.2
499.5	0.13	0.46	0.2
500.0	0.13	0.53	0.2
500.5	0.14	0.60	32.0
501.0	0.15	0.67	90.2
501.5	0.17	0.75	165.6
502.0	0.18	0.84	254.8
502.5	0.19	0.93	356.0
503.0	0.20	1.03	467.9
503.5	0.22	1.14	589.6
504.0	0.23	1.25	720.3
504.5	0.24	1.37	859.4
505.0	0.26	1.49	1006.5
505.5	0.27	1.62	1161.2
506.0	0.29	1.76	1323.1
506.5	0.30	1.91	1491.8
507.0	0.32	2.07	1667.2
507.5	0.34	2.23	1848.9
508.0	0.35	2.40	2036.8
508.5	0.37	2.59	2230.7
509.0	0.39	2.78	2430.4
509.5	0.41	2.97	2635.7
510.0	0.42	3.18	2846.4

Pond I.D. **10% IC 85% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	0.16	0.00	0.0
496.5	0.16	0.08	0.1
497.0	0.16	0.16	0.1
497.5	0.16	0.24	0.2
498.0	0.16	0.32	0.2
498.5	0.16	0.40	0.2
499.0	0.16	0.48	0.2
499.5	0.16	0.56	0.2
500.0	0.16	0.64	0.3
500.5	0.17	0.73	32.1
501.0	0.19	0.82	90.3
501.5	0.20	0.91	165.6
502.0	0.21	1.02	254.9
502.5	0.22	1.12	356.1
503.0	0.24	1.24	468.0
503.5	0.25	1.36	589.7
504.0	0.27	1.49	720.4
504.5	0.28	1.63	859.5
505.0	0.30	1.77	1006.6
505.5	0.31	1.93	1161.3
506.0	0.33	2.09	1323.1
506.5	0.35	2.26	1491.9
507.0	0.36	2.43	1667.2
507.5	0.38	2.62	1849.0
508.0	0.40	2.81	2036.9
508.5	0.42	3.02	2230.8
509.0	0.44	3.23	2430.5
509.5	0.46	3.45	2635.8
510.0	0.47	3.69	2846.5

Pond I.D. **10% IC 95% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	0.18	0.00	0.0
496.5	0.18	0.09	0.1
497.0	0.18	0.18	0.1
497.5	0.18	0.27	0.2
498.0	0.18	0.36	0.2
498.5	0.18	0.45	0.2
499.0	0.18	0.54	0.2
499.5	0.18	0.63	0.3
500.0	0.18	0.72	0.3
500.5	0.19	0.81	32.1
501.0	0.21	0.91	90.3
501.5	0.22	1.02	165.7
502.0	0.23	1.13	254.9
502.5	0.25	1.25	356.1
503.0	0.26	1.38	468.0
503.5	0.28	1.51	589.7
504.0	0.29	1.65	720.4
504.5	0.31	1.80	859.5
505.0	0.32	1.96	1006.7
505.5	0.34	2.13	1161.3
506.0	0.36	2.30	1323.2
506.5	0.37	2.48	1491.9
507.0	0.39	2.67	1667.3
507.5	0.41	2.87	1849.0
508.0	0.43	3.08	2037.0
508.5	0.45	3.30	2230.8
509.0	0.47	3.53	2430.5
509.5	0.49	3.77	2635.8
510.0	0.51	4.02	2846.6

Pond I.D. **10% IC 115% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	0.22	0.00	0.0
496.5	0.22	0.11	0.1
497.0	0.22	0.22	0.2
497.5	0.22	0.33	0.2
498.0	0.22	0.44	0.2
498.5	0.22	0.55	0.3
499.0	0.22	0.65	0.3
499.5	0.22	0.76	0.3
500.0	0.22	0.87	0.3
500.5	0.23	0.98	32.2
501.0	0.25	1.10	90.4
501.5	0.26	1.23	165.7
502.0	0.28	1.36	255.0
502.5	0.29	1.51	356.2
503.0	0.31	1.66	468.1
503.5	0.32	1.81	589.8
504.0	0.34	1.98	720.5
504.5	0.36	2.15	859.6
505.0	0.37	2.33	1006.7
505.5	0.39	2.52	1161.4
506.0	0.41	2.72	1323.3
506.5	0.43	2.93	1492.0
507.0	0.45	3.15	1667.4
507.5	0.47	3.38	1849.1
508.0	0.49	3.62	2037.1
508.5	0.51	3.87	2230.9
509.0	0.53	4.12	2430.6
509.5	0.55	4.39	2635.9
510.0	0.57	4.67	2846.7

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **20% IC 70% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	0.40	0.00	0.0
496.5	0.40	0.20	0.2
497.0	0.40	0.40	0.3
497.5	0.40	0.60	0.4
498.0	0.40	0.80	0.4
498.5	0.40	1.00	0.5
499.0	0.40	1.19	0.5
499.5	0.40	1.39	0.6
500.0	0.40	1.59	0.6
500.5	0.42	1.80	32.5
501.0	0.44	2.01	90.7
501.5	0.45	2.23	166.1
502.0	0.47	2.46	255.3
502.5	0.49	2.71	356.6
503.0	0.51	2.96	468.5
503.5	0.54	3.22	590.2
504.0	0.56	3.49	720.9
504.5	0.58	3.78	860.0
505.0	0.60	4.07	1007.2
505.5	0.62	4.38	1161.8
506.0	0.65	4.70	1323.7
506.5	0.67	5.02	1492.5
507.0	0.69	5.36	1667.9
507.5	0.72	5.72	1849.6
508.0	0.74	6.08	2037.5
508.5	0.77	6.46	2231.4
509.0	0.79	6.85	2431.1
509.5	0.82	7.25	2636.4
510.0	0.84	7.67	2847.2

Pond I.D. **20% IC 85% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	0.48	0.00	0.0
496.5	0.48	0.24	0.3
497.0	0.48	0.48	0.4
497.5	0.48	0.73	0.5
498.0	0.48	0.97	0.5
498.5	0.48	1.21	0.6
499.0	0.48	1.45	0.7
499.5	0.48	1.69	0.7
500.0	0.48	1.93	0.8
500.5	0.50	2.18	32.6
501.0	0.52	2.44	90.8
501.5	0.55	2.71	166.2
502.0	0.57	2.98	255.5
502.5	0.59	3.27	356.7
503.0	0.61	3.57	468.7
503.5	0.63	3.88	590.3
504.0	0.66	4.21	721.1
504.5	0.68	4.54	860.2
505.0	0.70	4.89	1007.4
505.5	0.73	5.25	1162.0
506.0	0.75	5.62	1323.9
506.5	0.78	6.00	1492.7
507.0	0.80	6.39	1668.1
507.5	0.83	6.80	1849.8
508.0	0.86	7.22	2037.8
508.5	0.88	7.66	2231.7
509.0	0.91	8.11	2431.4
509.5	0.94	8.57	2636.7
510.0	0.97	9.05	2847.5

Pond I.D. **20% IC 95% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	0.54	0.00	0.0
496.5	0.54	0.27	0.3
497.0	0.54	0.54	0.4
497.5	0.54	0.81	0.5
498.0	0.54	1.08	0.6
498.5	0.54	1.35	0.7
499.0	0.54	1.62	0.7
499.5	0.54	1.89	0.8
500.0	0.54	2.16	0.8
500.5	0.56	2.44	32.7
501.0	0.58	2.72	90.9
501.5	0.61	3.02	166.3
502.0	0.63	3.33	255.6
502.5	0.65	3.65	356.8
503.0	0.67	3.98	468.8
503.5	0.70	4.32	590.5
504.0	0.72	4.68	721.2
504.5	0.75	5.05	860.4
505.0	0.77	5.43	1007.5
505.5	0.80	5.82	1162.2
506.0	0.82	6.23	1324.1
506.5	0.85	6.64	1492.8
507.0	0.88	7.08	1668.2
507.5	0.90	7.52	1850.0
508.0	0.93	7.98	2037.9
508.5	0.96	8.45	2231.8
509.0	0.99	8.94	2431.5
509.5	1.02	9.44	2636.8
510.0	1.05	9.96	2847.6

Pond I.D. **20% IC 115% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	0.65	0.00	0.0
496.5	0.65	0.33	0.4
497.0	0.65	0.65	0.5
497.5	0.65	0.98	0.6
498.0	0.65	1.31	0.7
498.5	0.65	1.64	0.8
499.0	0.65	1.96	0.9
499.5	0.65	2.29	1.0
500.0	0.65	2.62	1.0
500.5	0.68	2.95	32.9
501.0	0.70	3.30	91.1
501.5	0.73	3.65	166.5
502.0	0.75	4.02	255.8
502.5	0.78	4.40	357.1
503.0	0.80	4.80	469.0
503.5	0.83	5.20	590.7
504.0	0.85	5.62	721.4
504.5	0.88	6.06	860.6
505.0	0.91	6.50	1007.8
505.5	0.94	6.97	1162.5
506.0	0.96	7.44	1324.3
506.5	0.99	7.93	1493.1
507.0	1.02	8.43	1668.5
507.5	1.05	8.95	1850.3
508.0	1.08	9.48	2038.2
508.5	1.11	10.03	2232.2
509.0	1.14	10.59	2431.8
509.5	1.17	11.17	2637.2
510.0	1.20	11.76	2848.0

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **30% IC 70% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	0.65	0.00	0.0
496.5	0.65	0.33	0.4
497.0	0.65	0.65	0.5
497.5	0.65	0.98	0.6
498.0	0.65	1.30	0.7
498.5	0.65	1.63	0.8
499.0	0.65	1.96	0.9
499.5	0.65	2.28	1.0
500.0	0.65	2.61	1.0
500.5	0.68	2.94	32.9
501.0	0.70	3.28	91.1
501.5	0.72	3.64	166.5
502.0	0.75	4.01	255.8
502.5	0.77	4.39	357.1
503.0	0.80	4.78	469.0
503.5	0.82	5.19	590.7
504.0	0.85	5.61	721.4
504.5	0.88	6.04	860.6
505.0	0.90	6.48	1007.8
505.5	0.93	6.94	1162.5
506.0	0.96	7.42	1324.3
506.5	0.99	7.90	1493.1
507.0	1.02	8.41	1668.5
507.5	1.05	8.92	1850.3
508.0	1.08	9.45	2038.2
508.5	1.11	10.00	2232.1
509.0	1.14	10.56	2431.8
509.5	1.17	11.14	2637.2
510.0	1.20	11.73	2848.0

Pond I.D. **30% IC 85% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	0.79	0.00	0.0
496.5	0.79	0.40	0.4
497.0	0.79	0.79	0.6
497.5	0.79	1.19	0.8
498.0	0.79	1.58	0.9
498.5	0.79	1.98	1.0
499.0	0.79	2.38	1.1
499.5	0.79	2.77	1.2
500.0	0.79	3.17	1.2
500.5	0.82	3.57	33.1
501.0	0.84	3.99	91.4
501.5	0.87	4.41	166.8
502.0	0.90	4.86	256.1
502.5	0.93	5.31	357.3
503.0	0.95	5.78	469.3
503.5	0.98	6.26	591.0
504.0	1.01	6.76	721.8
504.5	1.04	7.27	860.9
505.0	1.07	7.80	1008.1
505.5	1.10	8.34	1162.8
506.0	1.13	8.90	1324.7
506.5	1.16	9.47	1493.5
507.0	1.19	10.06	1668.9
507.5	1.22	10.66	1850.7
508.0	1.25	11.28	2038.6
508.5	1.29	11.92	2232.5
509.0	1.32	12.57	2432.2
509.5	1.35	13.24	2637.6
510.0	1.39	13.92	2848.4

Pond I.D. **30% IC 95% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	0.89	0.00	0.0
496.5	0.89	0.44	0.5
497.0	0.89	0.89	0.7
497.5	0.89	1.33	0.8
498.0	0.89	1.77	1.0
498.5	0.89	2.21	1.1
499.0	0.89	2.66	1.2
499.5	0.89	3.10	1.3
500.0	0.89	3.54	1.4
500.5	0.91	3.99	33.3
501.0	0.94	4.45	91.5
501.5	0.97	4.93	167.0
502.0	1.00	5.42	256.3
502.5	1.03	5.93	357.5
503.0	1.05	6.45	469.5
503.5	1.08	6.98	591.2
504.0	1.11	7.53	722.0
504.5	1.15	8.10	861.2
505.0	1.18	8.68	1008.3
505.5	1.21	9.27	1163.0
506.0	1.24	9.88	1324.9
506.5	1.27	10.51	1493.7
507.0	1.30	11.16	1669.1
507.5	1.34	11.82	1850.9
508.0	1.37	12.49	2038.9
508.5	1.40	13.19	2232.8
509.0	1.44	13.90	2432.5
509.5	1.47	14.63	2637.8
510.0	1.51	15.37	2848.6

Pond I.D. **30% IC 115% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	1.07	0.00	0.0
496.5	1.07	0.54	0.6
497.0	1.07	1.07	0.8
497.5	1.07	1.61	1.0
498.0	1.07	2.14	1.2
498.5	1.07	2.68	1.3
499.0	1.07	3.21	1.5
499.5	1.07	3.75	1.6
500.0	1.07	4.29	1.7
500.5	1.10	4.83	33.6
501.0	1.13	5.39	91.9
501.5	1.16	5.96	167.3
502.0	1.19	6.55	256.6
502.5	1.23	7.15	357.9
503.0	1.26	7.78	469.9
503.5	1.29	8.41	591.6
504.0	1.32	9.07	722.4
504.5	1.36	9.73	861.6
505.0	1.39	10.42	1008.7
505.5	1.42	11.12	1163.5
506.0	1.46	11.85	1325.4
506.5	1.49	12.58	1494.2
507.0	1.53	13.34	1669.6
507.5	1.56	14.11	1851.4
508.0	1.60	14.90	2039.4
508.5	1.64	15.71	2233.3
509.0	1.67	16.54	2433.0
509.5	1.71	17.39	2638.4
510.0	1.75	18.25	2849.2

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **40% IC 70% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	0.91	0.00	0.0
496.5	0.91	0.45	0.5
497.0	0.91	0.91	0.7
497.5	0.91	1.36	0.9
498.0	0.91	1.81	1.0
498.5	0.91	2.27	1.1
499.0	0.91	2.72	1.2
499.5	0.91	3.17	1.3
500.0	0.91	3.62	1.4
500.5	0.93	4.08	33.3
501.0	0.96	4.56	91.6
501.5	0.99	5.05	167.0
502.0	1.02	5.55	256.3
502.5	1.05	6.06	357.6
503.0	1.08	6.60	469.5
503.5	1.11	7.14	591.3
504.0	1.14	7.70	722.0
504.5	1.17	8.28	861.2
505.0	1.20	8.87	1008.4
505.5	1.23	9.48	1163.1
506.0	1.26	10.11	1325.0
506.5	1.30	10.75	1493.8
507.0	1.33	11.40	1669.2
507.5	1.36	12.08	1851.0
508.0	1.40	12.77	2038.9
508.5	1.43	13.47	2232.8
509.0	1.47	14.20	2432.6
509.5	1.50	14.94	2637.9
510.0	1.54	15.70	2848.7

Pond I.D. **40% IC 85% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	1.10	0.00	0.0
496.5	1.10	0.55	0.6
497.0	1.10	1.10	0.9
497.5	1.10	1.65	1.1
498.0	1.10	2.20	1.2
498.5	1.10	2.75	1.4
499.0	1.10	3.30	1.5
499.5	1.10	3.85	1.6
500.0	1.10	4.40	1.7
500.5	1.13	4.96	33.6
501.0	1.16	5.53	91.9
501.5	1.19	6.12	167.4
502.0	1.22	6.72	256.7
502.5	1.26	7.34	358.0
503.0	1.29	7.98	469.9
503.5	1.32	8.63	591.7
504.0	1.35	9.30	722.4
504.5	1.39	9.99	861.6
505.0	1.42	10.69	1008.8
505.5	1.46	11.41	1163.5
506.0	1.49	12.15	1325.4
506.5	1.53	12.90	1494.3
507.0	1.56	13.67	1669.7
507.5	1.60	14.47	1851.5
508.0	1.64	15.27	2039.5
508.5	1.67	16.10	2233.4
509.0	1.71	16.95	2433.1
509.5	1.75	17.81	2638.5
510.0	1.79	18.69	2849.3

Pond I.D. **40% IC 95% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	1.23	0.00	0.0
496.5	1.23	0.61	0.7
497.0	1.23	1.23	1.0
497.5	1.23	1.84	1.2
498.0	1.23	2.46	1.4
498.5	1.23	3.07	1.5
499.0	1.23	3.69	1.7
499.5	1.23	4.30	1.8
500.0	1.23	4.92	1.9
500.5	1.26	5.54	33.9
501.0	1.29	6.18	92.2
501.5	1.33	6.84	167.6
502.0	1.36	7.51	256.9
502.5	1.39	8.20	358.2
503.0	1.43	8.90	470.2
503.5	1.46	9.63	591.9
504.0	1.50	10.37	722.7
504.5	1.53	11.12	861.9
505.0	1.57	11.90	1009.1
505.5	1.61	12.69	1163.8
506.0	1.64	13.50	1325.8
506.5	1.68	14.33	1494.6
507.0	1.72	15.18	1670.0
507.5	1.75	16.05	1851.8
508.0	1.79	16.94	2039.8
508.5	1.83	17.84	2233.7
509.0	1.87	18.77	2433.5
509.5	1.91	19.71	2638.8
510.0	1.95	20.68	2849.7

Pond I.D. **40% IC 115% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	1.49	0.00	0.0
496.5	1.49	0.74	0.8
497.0	1.49	1.49	1.2
497.5	1.49	2.23	1.4
498.0	1.49	2.98	1.6
498.5	1.49	3.72	1.8
499.0	1.49	4.47	2.0
499.5	1.49	5.21	2.2
500.0	1.49	5.95	2.3
500.5	1.52	6.71	34.3
501.0	1.56	7.48	92.6
501.5	1.60	8.27	168.1
502.0	1.63	9.07	257.4
502.5	1.67	9.90	358.7
503.0	1.71	10.74	470.7
503.5	1.74	11.61	592.5
504.0	1.78	12.49	723.3
504.5	1.82	13.39	862.5
505.0	1.86	14.31	1009.7
505.5	1.90	15.25	1164.5
506.0	1.94	16.21	1326.4
506.5	1.98	17.19	1495.2
507.0	2.02	18.19	1670.7
507.5	2.06	19.21	1852.5
508.0	2.10	20.25	2040.5
508.5	2.14	21.31	2234.5
509.0	2.19	22.39	2434.2
509.5	2.23	23.50	2639.6
510.0	2.27	24.62	2850.4

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **50% IC 70% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	1.16	0.00	0.0
496.5	1.16	0.58	0.6
497.0	1.16	1.16	0.9
497.5	1.16	1.74	1.1
498.0	1.16	2.32	1.3
498.5	1.16	2.90	1.4
499.0	1.16	3.48	1.6
499.5	1.16	4.06	1.7
500.0	1.16	4.64	1.8
500.5	1.19	5.23	33.7
501.0	1.22	5.83	92.0
501.5	1.25	6.45	167.5
502.0	1.29	7.09	256.8
502.5	1.32	7.74	358.1
503.0	1.35	8.41	470.1
503.5	1.39	9.09	591.8
504.0	1.42	9.79	722.6
504.5	1.46	10.51	861.8
505.0	1.49	11.25	1009.0
505.5	1.53	12.00	1163.7
506.0	1.56	12.77	1325.6
506.5	1.60	13.56	1494.4
507.0	1.63	14.37	1669.8
507.5	1.67	15.20	1851.6
508.0	1.71	16.04	2039.6
508.5	1.75	16.91	2233.5
509.0	1.78	17.79	2433.3
509.5	1.82	18.69	2638.6
510.0	1.86	19.61	2849.4

Pond I.D. **50% IC 85% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	1.41	0.00	0.0
496.5	1.41	0.70	0.8
497.0	1.41	1.41	1.1
497.5	1.41	2.11	1.4
498.0	1.41	2.82	1.6
498.5	1.41	3.52	1.7
499.0	1.41	4.23	1.9
499.5	1.41	4.93	2.1
500.0	1.41	5.63	2.2
500.5	1.44	6.35	34.2
501.0	1.48	7.08	92.5
501.5	1.51	7.82	167.9
502.0	1.55	8.59	257.3
502.5	1.58	9.37	358.6
503.0	1.62	10.17	470.6
503.5	1.66	10.99	592.3
504.0	1.69	11.83	723.1
504.5	1.73	12.69	862.3
505.0	1.77	13.56	1009.5
505.5	1.81	14.46	1164.3
506.0	1.85	15.37	1326.2
506.5	1.89	16.31	1495.0
507.0	1.93	17.26	1670.5
507.5	1.97	18.23	1852.3
508.0	2.01	19.23	2040.3
508.5	2.05	20.24	2234.2
509.0	2.09	21.28	2434.0
509.5	2.13	22.33	2639.3
510.0	2.17	23.41	2850.2

Pond I.D. **50% IC 95% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	1.57	0.00	0.0
496.5	1.57	0.79	0.9
497.0	1.57	1.57	1.2
497.5	1.57	2.36	1.5
498.0	1.57	3.15	1.7
498.5	1.57	3.94	1.9
499.0	1.57	4.72	2.1
499.5	1.57	5.51	2.3
500.0	1.57	6.30	2.5
500.5	1.61	7.09	34.4
501.0	1.65	7.91	92.8
501.5	1.68	8.74	168.2
502.0	1.72	9.59	257.6
502.5	1.76	10.46	358.9
503.0	1.80	11.35	470.9
503.5	1.84	12.26	592.7
504.0	1.88	13.19	723.5
504.5	1.92	14.14	862.7
505.0	1.96	15.10	1009.9
505.5	2.00	16.09	1164.7
506.0	2.04	17.10	1326.6
506.5	2.08	18.13	1495.5
507.0	2.12	19.18	1670.9
507.5	2.16	20.25	1852.7
508.0	2.20	21.34	2040.7
508.5	2.25	22.45	2234.7
509.0	2.29	23.59	2434.4
509.5	2.33	24.74	2639.8
510.0	2.38	25.92	2850.7

Pond I.D. **50% IC 115% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	1.91	0.00	0.0
496.5	1.91	0.95	1.1
497.0	1.91	1.91	1.5
497.5	1.91	2.86	1.8
498.0	1.91	3.81	2.1
498.5	1.91	4.76	2.4
499.0	1.91	5.72	2.6
499.5	1.91	6.67	2.8
500.0	1.91	7.62	3.0
500.5	1.95	8.59	35.0
501.0	1.99	9.57	93.3
501.5	2.03	10.57	168.8
502.0	2.07	11.60	258.2
502.5	2.11	12.64	359.6
503.0	2.15	13.70	471.6
503.5	2.19	14.79	593.4
504.0	2.24	15.90	724.2
504.5	2.28	17.03	863.5
505.0	2.32	18.18	1010.7
505.5	2.37	19.35	1165.5
506.0	2.41	20.55	1327.4
506.5	2.46	21.76	1496.3
507.0	2.50	23.00	1671.8
507.5	2.55	24.26	1853.6
508.0	2.59	25.55	2041.6
508.5	2.64	26.86	2235.6
509.0	2.69	28.19	2435.4
509.5	2.73	29.54	2640.8
510.0	2.78	30.92	2851.6

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **60% IC 60% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	1.35	0.00	0.0
496.5	1.35	0.67	0.7
497.0	1.35	1.35	1.1
497.5	1.35	2.02	1.3
498.0	1.35	2.70	1.5
498.5	1.35	3.37	1.7
499.0	1.35	4.04	1.8
499.5	1.35	4.72	2.0
500.0	1.35	5.39	2.1
500.5	1.38	6.07	34.1
501.0	1.42	6.77	92.4
501.5	1.45	7.49	167.8
502.0	1.48	8.22	257.1
502.5	1.52	8.97	358.4
503.0	1.56	9.74	470.4
503.5	1.59	10.53	592.2
504.0	1.63	11.33	723.0
504.5	1.66	12.16	862.2
505.0	1.70	13.00	1009.4
505.5	1.74	13.86	1164.1
506.0	1.78	14.74	1326.1
506.5	1.82	15.64	1494.9
507.0	1.86	16.56	1670.3
507.5	1.89	17.49	1852.1
508.0	1.93	18.45	2040.1
508.5	1.97	19.43	2234.1
509.0	2.02	20.43	2433.8
509.5	2.06	21.44	2639.2
510.0	2.10	22.48	2850.0

Pond I.D. **60% IC 70% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	1.57	0.00	0.0
496.5	1.57	0.79	0.9
497.0	1.57	1.57	1.2
497.5	1.57	2.36	1.5
498.0	1.57	3.14	1.7
498.5	1.57	3.93	1.9
499.0	1.57	4.72	2.1
499.5	1.57	5.50	2.3
500.0	1.57	6.29	2.5
500.5	1.61	7.09	34.4
501.0	1.65	7.90	92.8
501.5	1.68	8.73	168.2
502.0	1.72	9.58	257.6
502.5	1.76	10.45	358.9
503.0	1.80	11.34	470.9
503.5	1.83	12.25	592.7
504.0	1.87	13.17	723.5
504.5	1.91	14.12	862.7
505.0	1.95	15.09	1009.9
505.5	1.99	16.07	1164.7
506.0	2.03	17.08	1326.6
506.5	2.08	18.11	1495.5
507.0	2.12	19.16	1670.9
507.5	2.16	20.23	1852.7
508.0	2.20	21.32	2040.7
508.5	2.25	22.43	2234.7
509.0	2.29	23.56	2434.4
509.5	2.33	24.72	2639.8
510.0	2.38	25.90	2850.7

Pond I.D. **60% IC 85% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	1.91	0.00	0.0
496.5	1.91	0.95	1.1
497.0	1.91	1.91	1.5
497.5	1.91	2.86	1.8
498.0	1.91	3.82	2.1
498.5	1.91	4.77	2.4
499.0	1.91	5.73	2.6
499.5	1.91	6.68	2.8
500.0	1.91	7.64	3.0
500.5	1.95	8.60	35.0
501.0	1.99	9.59	93.3
501.5	2.03	10.59	168.8
502.0	2.07	11.62	258.2
502.5	2.11	12.66	359.6
503.0	2.16	13.73	471.6
503.5	2.20	14.82	593.4
504.0	2.24	15.93	724.2
504.5	2.28	17.06	863.5
505.0	2.33	18.21	1010.7
505.5	2.37	19.39	1165.5
506.0	2.42	20.58	1327.5
506.5	2.46	21.80	1496.3
507.0	2.51	23.04	1671.8
507.5	2.55	24.31	1853.6
508.0	2.60	25.60	2041.6
508.5	2.64	26.91	2235.6
509.0	2.69	28.24	2435.4
509.5	2.74	29.60	2640.8
510.0	2.79	30.98	2851.6

Pond I.D. **60% IC 95% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	2.13	0.00	0.0
496.5	2.13	1.07	1.2
497.0	2.13	2.13	1.7
497.5	2.13	3.20	2.0
498.0	2.13	4.27	2.4
498.5	2.13	5.34	2.6
499.0	2.13	6.40	2.9
499.5	2.13	7.47	3.1
500.0	2.13	8.54	3.3
500.5	2.18	9.61	35.4
501.0	2.22	10.71	93.7
501.5	2.26	11.83	169.3
502.0	2.31	12.97	258.7
502.5	2.35	14.14	360.0
503.0	2.39	15.32	472.1
503.5	2.44	16.53	593.9
504.0	2.48	17.76	724.7
504.5	2.53	19.02	864.0
505.0	2.57	20.29	1011.2
505.5	2.62	21.59	1166.0
506.0	2.67	22.91	1328.0
506.5	2.71	24.26	1496.9
507.0	2.76	25.63	1672.4
507.5	2.81	27.02	1854.2
508.0	2.86	28.44	2042.3
508.5	2.91	29.88	2236.2
509.0	2.96	31.35	2436.0
509.5	3.01	32.84	2641.4
510.0	3.06	34.35	2852.3

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **60% IC 115% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	2.58	0.00	0.0
496.5	2.58	1.29	1.4
497.0	2.58	2.58	2.0
497.5	2.58	3.88	2.5
498.0	2.58	5.17	2.9
498.5	2.58	6.46	3.2
499.0	2.58	7.75	3.5
499.5	2.58	9.04	3.8
500.0	2.58	10.33	4.0
500.5	2.63	11.64	36.1
501.0	2.68	12.96	94.5
501.5	2.72	14.31	170.1
502.0	2.77	15.69	259.5
502.5	2.82	17.08	360.9
503.0	2.87	18.51	473.0
503.5	2.92	19.95	594.8
504.0	2.97	21.42	725.7
504.5	3.02	22.92	865.0
505.0	3.07	24.44	1012.3
505.5	3.12	25.99	1167.1
506.0	3.17	27.56	1329.1
506.5	3.22	29.15	1498.0
507.0	3.27	30.78	1673.5
507.5	3.32	32.42	1855.4
508.0	3.38	34.10	2043.5
508.5	3.43	35.80	2237.5
509.0	3.48	37.53	2437.3
509.5	3.54	39.28	2642.7
510.0	3.59	41.06	2853.6

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **75% IC 60% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	1.88	0.00	0.0
496.5	1.88	0.94	1.0
497.0	1.88	1.88	1.5
497.5	1.88	2.82	1.8
498.0	1.88	3.76	2.1
498.5	1.88	4.70	2.3
499.0	1.88	5.63	2.5
499.5	1.88	6.57	2.8
500.0	1.88	7.51	2.9
500.5	1.92	8.46	34.9
501.0	1.96	9.43	93.3
501.5	2.00	10.42	168.8
502.0	2.04	11.43	258.2
502.5	2.08	12.46	359.5
503.0	2.12	13.51	471.5
503.5	2.16	14.58	593.3
504.0	2.21	15.67	724.2
504.5	2.25	16.79	863.4
505.0	2.29	17.92	1010.6
505.5	2.34	19.08	1165.4
506.0	2.38	20.26	1327.4
506.5	2.43	21.46	1496.2
507.0	2.47	22.68	1671.7
507.5	2.52	23.93	1853.5
508.0	2.56	25.20	2041.6
508.5	2.61	26.49	2235.5
509.0	2.65	27.81	2435.3
509.5	2.70	29.15	2640.7
510.0	2.75	30.51	2851.6

Pond I.D. **75% IC 70% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	2.19	0.00	0.0
496.5	2.19	1.10	1.2
497.0	2.19	2.19	1.7
497.5	2.19	3.29	2.1
498.0	2.19	4.38	2.4
498.5	2.19	5.48	2.7
499.0	2.19	6.57	3.0
499.5	2.19	7.67	3.2
500.0	2.19	8.76	3.4
500.5	2.23	9.87	35.5
501.0	2.28	11.00	93.8
501.5	2.32	12.15	169.4
502.0	2.36	13.32	258.8
502.5	2.41	14.51	360.1
503.0	2.45	15.73	472.2
503.5	2.50	16.97	594.0
504.0	2.54	18.23	724.9
504.5	2.59	19.51	864.1
505.0	2.64	20.82	1011.4
505.5	2.68	22.15	1166.2
506.0	2.73	23.50	1328.1
506.5	2.78	24.88	1497.0
507.0	2.83	26.28	1672.5
507.5	2.88	27.71	1854.4
508.0	2.92	29.16	2042.4
508.5	2.97	30.63	2236.4
509.0	3.02	32.13	2436.2
509.5	3.07	33.66	2641.6
510.0	3.12	35.21	2852.5

Pond I.D. **75% IC 85% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	2.66	0.00	0.0
496.5	2.66	1.33	1.5
497.0	2.66	2.66	2.1
497.5	2.66	3.99	2.6
498.0	2.66	5.32	2.9
498.5	2.66	6.65	3.3
499.0	2.66	7.98	3.6
499.5	2.66	9.31	3.9
500.0	2.66	10.64	4.2
500.5	2.71	11.99	36.2
501.0	2.76	13.35	94.7
501.5	2.80	14.74	170.2
502.0	2.85	16.15	259.7
502.5	2.90	17.59	361.1
503.0	2.95	19.05	473.2
503.5	3.00	20.54	595.0
504.0	3.05	22.05	725.9
504.5	3.10	23.59	865.2
505.0	3.15	25.15	1012.5
505.5	3.20	26.74	1167.3
506.0	3.25	28.36	1329.3
506.5	3.31	29.99	1498.2
507.0	3.36	31.66	1673.7
507.5	3.41	33.35	1855.6
508.0	3.46	35.07	2043.7
508.5	3.52	36.82	2237.7
509.0	3.57	38.59	2437.5
509.5	3.63	40.39	2642.9
510.0	3.68	42.22	2853.8

Pond I.D. **75% IC 95% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	2.97	0.00	0.0
496.5	2.97	1.49	1.6
497.0	2.97	2.97	2.3
497.5	2.97	4.46	2.9
498.0	2.97	5.95	3.3
498.5	2.97	7.43	3.7
499.0	2.97	8.92	4.0
499.5	2.97	10.41	4.4
500.0	2.97	11.89	4.7
500.5	3.02	13.39	36.8
501.0	3.07	14.92	95.2
501.5	3.12	16.47	170.8
502.0	3.18	18.04	260.3
502.5	3.23	19.64	361.7
503.0	3.28	21.27	473.8
503.5	3.33	22.92	595.7
504.0	3.38	24.60	726.6
504.5	3.44	26.31	865.9
505.0	3.49	28.04	1013.2
505.5	3.54	29.80	1168.1
506.0	3.60	31.58	1330.1
506.5	3.65	33.39	1499.0
507.0	3.71	35.24	1674.5
507.5	3.76	37.10	1856.5
508.0	3.82	39.00	2044.5
508.5	3.88	40.92	2238.6
509.0	3.93	42.88	2438.4
509.5	3.99	44.86	2643.8
510.0	4.05	46.87	2854.8

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **75% IC 115% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	3.60	0.00	0.0
496.5	3.60	1.80	2.0
497.0	3.60	3.60	2.8
497.5	3.60	5.40	3.5
498.0	3.60	7.20	4.0
498.5	3.60	9.00	4.5
499.0	3.60	10.80	4.9
499.5	3.60	12.60	5.3
500.0	3.60	14.40	5.6
500.5	3.65	16.21	37.8
501.0	3.71	18.05	96.3
501.5	3.77	19.92	171.9
502.0	3.82	21.82	261.5
502.5	3.88	23.74	362.9
503.0	3.93	25.70	475.1
503.5	3.99	27.68	597.0
504.0	4.05	29.69	728.0
504.5	4.11	31.73	867.4
505.0	4.17	33.80	1014.7
505.5	4.22	35.89	1169.6
506.0	4.28	38.02	1331.6
506.5	4.34	40.18	1500.6
507.0	4.40	42.37	1676.2
507.5	4.46	44.58	1858.1
508.0	4.53	46.83	2046.2
508.5	4.59	49.11	2240.3
509.0	4.65	51.42	2440.2
509.5	4.71	53.76	2645.6
510.0	4.77	56.13	2856.6

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **85% IC 50% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	1.86	0.00	0.0
496.5	1.86	0.93	1.0
497.0	1.86	1.86	1.5
497.5	1.86	2.79	1.8
498.0	1.86	3.72	2.1
498.5	1.86	4.65	2.3
499.0	1.86	5.58	2.5
499.5	1.86	6.51	2.7
500.0	1.86	7.44	2.9
500.5	1.90	8.38	34.9
501.0	1.94	9.34	93.3
501.5	1.98	10.32	168.8
502.0	2.02	11.32	258.1
502.5	2.06	12.34	359.5
503.0	2.10	13.38	471.5
503.5	2.14	14.44	593.3
504.0	2.19	15.52	724.1
504.5	2.23	16.63	863.4
505.0	2.27	17.75	1010.6
505.5	2.32	18.90	1165.4
506.0	2.36	20.07	1327.3
506.5	2.40	21.26	1496.2
507.0	2.45	22.47	1671.7
507.5	2.49	23.71	1853.5
508.0	2.54	24.97	2041.5
508.5	2.59	26.25	2235.5
509.0	2.63	27.55	2435.2
509.5	2.68	28.88	2640.6
510.0	2.73	30.23	2851.5

Pond I.D. **85% IC 60% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	2.23	0.00	0.0
496.5	2.23	1.12	1.2
497.0	2.23	2.23	1.7
497.5	2.23	3.35	2.1
498.0	2.23	4.46	2.5
498.5	2.23	5.58	2.8
499.0	2.23	6.70	3.0
499.5	2.23	7.81	3.3
500.0	2.23	8.93	3.5
500.5	2.27	10.05	35.5
501.0	2.32	11.20	93.9
501.5	2.36	12.37	169.4
502.0	2.41	13.56	258.8
502.5	2.45	14.78	360.2
503.0	2.50	16.02	472.3
503.5	2.54	17.28	594.1
504.0	2.59	18.56	724.9
504.5	2.63	19.86	864.2
505.0	2.68	21.19	1011.5
505.5	2.73	22.55	1166.3
506.0	2.78	23.92	1328.2
506.5	2.82	25.32	1497.1
507.0	2.87	26.75	1672.6
507.5	2.92	28.20	1854.5
508.0	2.97	29.67	2042.5
508.5	3.02	31.17	2236.5
509.0	3.07	32.69	2436.3
509.5	3.12	34.24	2641.7
510.0	3.17	35.81	2852.6

Pond I.D. **85% IC 70% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	2.60	0.00	0.0
496.5	2.60	1.30	1.4
497.0	2.60	2.60	2.0
497.5	2.60	3.91	2.5
498.0	2.60	5.21	2.9
498.5	2.60	6.51	3.2
499.0	2.60	7.81	3.5
499.5	2.60	9.11	3.8
500.0	2.60	10.41	4.1
500.5	2.65	11.73	36.1
501.0	2.70	13.07	94.6
501.5	2.74	14.43	170.1
502.0	2.79	15.81	259.6
502.5	2.84	17.22	361.0
503.0	2.89	18.65	473.0
503.5	2.94	20.11	594.9
504.0	2.99	21.59	725.8
504.5	3.04	23.10	865.1
505.0	3.09	24.63	1012.3
505.5	3.14	26.18	1167.2
506.0	3.19	27.77	1329.2
506.5	3.24	29.37	1498.1
507.0	3.29	31.01	1673.6
507.5	3.35	32.67	1855.5
508.0	3.40	34.35	2043.5
508.5	3.45	36.07	2237.5
509.0	3.51	37.81	2437.3
509.5	3.56	39.57	2642.8
510.0	3.61	41.37	2853.7

Pond I.D. **85% IC 85% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	3.16	0.00	0.0
496.5	3.16	1.58	1.8
497.0	3.16	3.16	2.5
497.5	3.16	4.74	3.0
498.0	3.16	6.32	3.5
498.5	3.16	7.90	3.9
499.0	3.16	9.48	4.3
499.5	3.16	11.07	4.6
500.0	3.16	12.65	5.0
500.5	3.21	14.24	37.1
501.0	3.26	15.86	95.5
501.5	3.32	17.50	171.1
502.0	3.37	19.18	260.6
502.5	3.42	20.87	362.1
503.0	3.48	22.60	474.2
503.5	3.53	24.35	596.1
504.0	3.58	26.13	727.0
504.5	3.64	27.93	866.4
505.0	3.69	29.77	1013.7
505.5	3.75	31.63	1168.5
506.0	3.80	33.52	1330.6
506.5	3.86	35.43	1499.5
507.0	3.92	37.38	1675.0
507.5	3.97	39.35	1857.0
508.0	4.03	41.35	2045.0
508.5	4.09	43.38	2239.1
509.0	4.15	45.44	2438.9
509.5	4.21	47.53	2644.4
510.0	4.27	49.65	2855.3

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **85% IC 95% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	3.53	0.00	0.0
496.5	3.53	1.77	2.0
497.0	3.53	3.53	2.8
497.5	3.53	5.30	3.4
498.0	3.53	7.07	3.9
498.5	3.53	8.83	4.4
499.0	3.53	10.60	4.8
499.5	3.53	12.37	5.2
500.0	3.53	14.13	5.5
500.5	3.59	15.91	37.7
501.0	3.64	17.72	96.2
501.5	3.70	19.56	171.8
502.0	3.75	21.42	261.3
502.5	3.81	23.31	362.8
503.0	3.87	25.23	475.0
503.5	3.92	27.18	596.9
504.0	3.98	29.15	727.8
504.5	4.04	31.15	867.2
505.0	4.09	33.19	1014.5
505.5	4.15	35.25	1169.4
506.0	4.21	37.34	1331.5
506.5	4.27	39.46	1500.4
507.0	4.33	41.61	1676.0
507.5	4.39	43.79	1857.9
508.0	4.45	46.00	2046.1
508.5	4.51	48.24	2240.1
509.0	4.57	50.51	2440.0
509.5	4.63	52.82	2645.5
510.0	4.70	55.15	2856.4

Pond I.D. **85% IC 115% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	4.28	0.00	0.0
496.5	4.28	2.14	2.4
497.0	4.28	4.28	3.3
497.5	4.28	6.42	4.1
498.0	4.28	8.55	4.7
498.5	4.28	10.69	5.3
499.0	4.28	12.83	5.8
499.5	4.28	14.97	6.3
500.0	4.28	17.11	6.7
500.5	4.34	19.26	38.9
501.0	4.40	21.45	97.5
501.5	4.46	23.66	173.2
502.0	4.52	25.90	262.8
502.5	4.58	28.18	364.3
503.0	4.64	30.48	476.5
503.5	4.70	32.82	598.5
504.0	4.77	35.19	729.5
504.5	4.83	37.59	868.9
505.0	4.89	40.02	1016.3
505.5	4.96	42.48	1171.2
506.0	5.02	44.97	1333.3
506.5	5.09	47.50	1502.3
507.0	5.15	50.06	1677.9
507.5	5.22	52.65	1859.9
508.0	5.28	55.28	2048.1
508.5	5.35	57.93	2242.2
509.0	5.41	60.62	2442.1
509.5	5.48	63.35	2647.6
510.0	5.55	66.11	2858.6

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **95% IC 50% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	2.15	0.00	0.0
496.5	2.15	1.08	1.2
497.0	2.15	2.15	1.7
497.5	2.15	3.23	2.1
498.0	2.15	4.31	2.4
498.5	2.15	5.39	2.7
499.0	2.15	6.46	2.9
499.5	2.15	7.54	3.2
500.0	2.15	8.62	3.4
500.5	2.20	9.71	35.4
501.0	2.24	10.81	93.8
501.5	2.28	11.94	169.3
502.0	2.33	13.10	258.7
502.5	2.37	14.27	360.1
503.0	2.41	15.47	472.1
503.5	2.46	16.69	593.9
504.0	2.51	17.93	724.8
504.5	2.55	19.19	864.1
505.0	2.60	20.48	1011.3
505.5	2.64	21.79	1166.1
506.0	2.69	23.12	1328.1
506.5	2.74	24.48	1496.9
507.0	2.79	25.86	1672.4
507.5	2.83	27.27	1854.3
508.0	2.88	28.69	2042.3
508.5	2.93	30.15	2236.3
509.0	2.98	31.63	2436.1
509.5	3.03	33.13	2641.5
510.0	3.08	34.66	2852.4

Pond I.D. **95% IC 60% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	2.59	0.00	0.0
496.5	2.59	1.29	1.4
497.0	2.59	2.59	2.0
497.5	2.59	3.88	2.5
498.0	2.59	5.17	2.9
498.5	2.59	6.46	3.2
499.0	2.59	7.76	3.5
499.5	2.59	9.05	3.8
500.0	2.59	10.34	4.0
500.5	2.63	11.65	36.1
501.0	2.68	12.97	94.5
501.5	2.73	14.32	170.1
502.0	2.77	15.70	259.5
502.5	2.82	17.10	360.9
503.0	2.87	18.52	473.0
503.5	2.92	19.97	594.9
504.0	2.97	21.44	725.7
504.5	3.02	22.94	865.0
505.0	3.07	24.46	1012.3
505.5	3.12	26.00	1167.1
506.0	3.17	27.58	1329.1
506.5	3.22	29.17	1498.0
507.0	3.27	30.80	1673.5
507.5	3.33	32.45	1855.4
508.0	3.38	34.12	2043.5
508.5	3.43	35.82	2237.5
509.0	3.48	37.55	2437.3
509.5	3.54	39.31	2642.7
510.0	3.59	41.09	2853.6

Pond I.D. **95% IC 70% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	3.02	0.00	0.0
496.5	3.02	1.51	1.7
497.0	3.02	3.02	2.4
497.5	3.02	4.52	2.9
498.0	3.02	6.03	3.3
498.5	3.02	7.54	3.7
499.0	3.02	9.05	4.1
499.5	3.02	10.56	4.4
500.0	3.02	12.06	4.7
500.5	3.07	13.59	36.8
501.0	3.12	15.13	95.3
501.5	3.17	16.70	170.9
502.0	3.22	18.30	260.3
502.5	3.27	19.92	361.8
503.0	3.32	21.57	473.9
503.5	3.38	23.24	595.8
504.0	3.43	24.95	726.7
504.5	3.48	26.67	866.0
505.0	3.54	28.43	1013.3
505.5	3.59	30.21	1168.2
506.0	3.65	32.02	1330.2
506.5	3.70	33.85	1499.1
507.0	3.76	35.72	1674.7
507.5	3.81	37.61	1856.6
508.0	3.87	39.53	2044.6
508.5	3.92	41.48	2238.7
509.0	3.98	43.46	2438.5
509.5	4.04	45.46	2644.0
510.0	4.10	47.49	2854.9

Pond I.D. **95% IC 85% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	3.66	0.00	0.0
496.5	3.66	1.83	2.0
497.0	3.66	3.66	2.9
497.5	3.66	5.49	3.5
498.0	3.66	7.32	4.1
498.5	3.66	9.16	4.5
499.0	3.66	10.99	5.0
499.5	3.66	12.82	5.4
500.0	3.66	14.65	5.7
500.5	3.72	16.49	37.9
501.0	3.77	18.37	96.4
501.5	3.83	20.27	172.1
502.0	3.89	22.20	261.6
502.5	3.94	24.15	363.1
503.0	4.00	26.14	475.2
503.5	4.06	28.15	597.2
504.0	4.12	30.20	728.1
504.5	4.17	32.27	867.5
505.0	4.23	34.37	1014.8
505.5	4.29	36.50	1169.7
506.0	4.35	38.66	1331.8
506.5	4.41	40.86	1500.8
507.0	4.47	43.08	1676.3
507.5	4.53	45.33	1858.3
508.0	4.60	47.61	2046.4
508.5	4.66	49.93	2240.5
509.0	4.72	52.27	2440.3
509.5	4.78	54.64	2645.8
510.0	4.85	57.05	2856.8

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **95% IC 95% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	4.09	0.00	0.0
496.5	4.09	2.05	2.3
497.0	4.09	4.09	3.2
497.5	4.09	6.14	3.9
498.0	4.09	8.19	4.5
498.5	4.09	10.23	5.1
499.0	4.09	12.28	5.6
499.5	4.09	14.33	6.0
500.0	4.09	16.37	6.4
500.5	4.15	18.43	38.6
501.0	4.21	20.53	97.2
501.5	4.27	22.65	172.9
502.0	4.33	24.79	262.4
502.5	4.39	26.97	363.9
503.0	4.45	29.18	476.1
503.5	4.51	31.42	598.1
504.0	4.57	33.70	729.1
504.5	4.63	36.00	868.5
505.0	4.70	38.33	1015.8
505.5	4.76	40.69	1170.8
506.0	4.82	43.09	1332.9
506.5	4.88	45.51	1501.8
507.0	4.95	47.97	1677.5
507.5	5.01	50.46	1859.4
508.0	5.08	52.98	2047.6
508.5	5.14	55.54	2241.7
509.0	5.21	58.13	2441.6
509.5	5.27	60.75	2647.1
510.0	5.34	63.40	2858.0

Pond I.D. **95% IC 115% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	4.96	0.00	0.0
496.5	4.96	2.48	2.7
497.0	4.96	4.96	3.9
497.5	4.96	7.43	4.8
498.0	4.96	9.91	5.5
498.5	4.96	12.39	6.1
499.0	4.96	14.87	6.7
499.5	4.96	17.34	7.3
500.0	4.96	19.82	7.8
500.5	5.02	22.31	40.0
501.0	5.08	24.84	98.7
501.5	5.15	27.40	174.4
502.0	5.21	29.99	264.1
502.5	5.28	32.61	365.6
503.0	5.35	35.27	477.9
503.5	5.41	37.96	599.9
504.0	5.48	40.68	731.0
504.5	5.55	43.44	870.4
505.0	5.62	46.23	1017.9
505.5	5.68	49.06	1172.8
506.0	5.75	51.91	1335.0
506.5	5.82	54.81	1504.0
507.0	5.89	57.74	1679.7
507.5	5.96	60.70	1861.7
508.0	6.03	63.70	2049.9
508.5	6.10	66.73	2244.1
509.0	6.17	69.80	2444.0
509.5	6.25	72.91	2649.5
510.0	6.32	76.05	2860.6

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **100% IC 50% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	2.30	0.00	0.0
496.5	2.30	1.15	1.3
497.0	2.30	2.30	1.8
497.5	2.30	3.45	2.2
498.0	2.30	4.60	2.5
498.5	2.30	5.75	2.8
499.0	2.30	6.91	3.1
499.5	2.30	8.06	3.4
500.0	2.30	9.21	3.6
500.5	2.35	10.37	35.6
501.0	2.39	11.55	94.0
501.5	2.43	12.76	169.6
502.0	2.48	13.99	259.0
502.5	2.52	15.24	360.4
503.0	2.57	16.51	472.4
503.5	2.62	17.81	594.2
504.0	2.66	19.13	725.1
504.5	2.71	20.47	864.4
505.0	2.76	21.84	1011.6
505.5	2.81	23.23	1166.4
506.0	2.85	24.65	1328.4
506.5	2.90	26.09	1497.3
507.0	2.95	27.55	1672.8
507.5	3.00	29.04	1854.7
508.0	3.05	30.55	2042.7
508.5	3.10	32.09	2236.7
509.0	3.15	33.66	2436.5
509.5	3.20	35.25	2641.9
510.0	3.26	36.86	2852.8

Pond I.D. **100% IC 60% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	2.76	0.00	0.0
496.5	2.76	1.38	1.5
497.0	2.76	2.76	2.2
497.5	2.76	4.14	2.6
498.0	2.76	5.52	3.1
498.5	2.76	6.91	3.4
499.0	2.76	8.29	3.7
499.5	2.76	9.67	4.0
500.0	2.76	11.05	4.3
500.5	2.81	12.44	36.4
501.0	2.86	13.86	94.8
501.5	2.91	15.30	170.4
502.0	2.96	16.77	259.9
502.5	3.01	18.26	361.3
503.0	3.06	19.77	473.4
503.5	3.11	21.31	595.2
504.0	3.16	22.88	726.1
504.5	3.21	24.47	865.4
505.0	3.26	26.09	1012.7
505.5	3.31	27.73	1167.5
506.0	3.37	29.40	1329.6
506.5	3.42	31.10	1498.5
507.0	3.47	32.82	1674.0
507.5	3.53	34.57	1855.9
508.0	3.58	36.34	2044.0
508.5	3.63	38.15	2238.0
509.0	3.69	39.98	2437.8
509.5	3.74	41.84	2643.2
510.0	3.80	43.72	2854.1

Pond I.D. **100% IC 70% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	3.22	0.00	0.0
496.5	3.22	1.61	1.8
497.0	3.22	3.22	2.5
497.5	3.22	4.83	3.1
498.0	3.22	6.44	3.6
498.5	3.22	8.06	4.0
499.0	3.22	9.67	4.4
499.5	3.22	11.28	4.7
500.0	3.22	12.89	5.0
500.5	3.27	14.51	37.2
501.0	3.33	16.16	95.6
501.5	3.38	17.84	171.3
502.0	3.43	19.54	260.7
502.5	3.49	21.27	362.2
503.0	3.54	23.03	474.3
503.5	3.59	24.81	596.2
504.0	3.65	26.62	727.1
504.5	3.70	28.46	866.5
505.0	3.76	30.33	1013.8
505.5	3.82	32.22	1168.7
506.0	3.87	34.14	1330.7
506.5	3.93	36.09	1499.6
507.0	3.99	38.07	1675.2
507.5	4.04	40.08	1857.1
508.0	4.10	42.11	2045.2
508.5	4.16	44.18	2239.3
509.0	4.22	46.27	2439.1
509.5	4.28	48.40	2644.6
510.0	4.34	50.55	2855.5

Pond I.D. **100% IC 85% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	3.91	0.00	0.0
496.5	3.91	1.96	2.2
497.0	3.91	3.91	3.1
497.5	3.91	5.87	3.8
498.0	3.91	7.83	4.3
498.5	3.91	9.78	4.8
499.0	3.91	11.74	5.3
499.5	3.91	13.70	5.7
500.0	3.91	15.65	6.1
500.5	3.97	17.62	38.3
501.0	4.03	19.62	96.8
501.5	4.09	21.65	172.5
502.0	4.14	23.71	262.1
502.5	4.20	25.79	363.6
503.0	4.26	27.91	475.8
503.5	4.32	30.06	597.7
504.0	4.38	32.23	728.7
504.5	4.44	34.44	868.1
505.0	4.50	36.67	1015.4
505.5	4.56	38.94	1170.3
506.0	4.63	41.24	1332.4
506.5	4.69	43.56	1501.4
507.0	4.75	45.92	1677.0
507.5	4.81	48.31	1859.0
508.0	4.88	50.74	2047.1
508.5	4.94	53.19	2241.2
509.0	5.00	55.67	2441.0
509.5	5.07	58.19	2646.5
510.0	5.13	60.74	2857.5

POND STAGE-STORAGE-DISCHARGE RELATIONSHIPS

Pond I.D. **100% IC 95% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	4.37	0.00	0.0
496.5	4.37	2.19	2.4
497.0	4.37	4.37	3.4
497.5	4.37	6.56	4.2
498.0	4.37	8.75	4.8
498.5	4.37	10.93	5.4
499.0	4.37	13.12	5.9
499.5	4.37	15.31	6.4
500.0	4.37	17.49	6.8
500.5	4.43	19.69	39.1
501.0	4.49	21.93	97.7
501.5	4.56	24.19	173.4
502.0	4.62	26.48	262.9
502.5	4.68	28.81	364.5
503.0	4.74	31.16	476.7
503.5	4.80	33.55	598.7
504.0	4.87	35.97	729.7
504.5	4.93	38.42	869.1
505.0	5.00	40.90	1016.5
505.5	5.06	43.41	1171.4
506.0	5.12	45.96	1333.6
506.5	5.19	48.53	1502.6
507.0	5.26	51.15	1678.2
507.5	5.32	53.79	1860.2
508.0	5.39	56.47	2048.3
508.5	5.45	59.18	2242.4
509.0	5.52	61.92	2442.3
509.5	5.59	64.70	2647.9
510.0	5.66	67.51	2858.9

Pond I.D. **100% IC 115% Vol**

Elevation	Area (acres)	Volume (ac-ft)	Total Discharge (cfs)
496.0	5.29	0.00	0.0
496.5	5.29	2.65	2.9
497.0	5.29	5.29	4.1
497.5	5.29	7.94	5.1
498.0	5.29	10.59	5.9
498.5	5.29	13.23	6.6
499.0	5.29	15.88	7.2
499.5	5.29	18.53	7.8
500.0	5.29	21.18	8.3
500.5	5.36	23.84	40.6
501.0	5.43	26.54	99.3
501.5	5.49	29.27	175.1
502.0	5.56	32.03	264.7
502.5	5.63	34.83	366.3
503.0	5.70	37.66	478.6
503.5	5.77	40.53	600.7
504.0	5.84	43.43	731.7
504.5	5.91	46.36	871.2
505.0	5.98	49.33	1018.7
505.5	6.05	52.34	1173.7
506.0	6.12	55.38	1335.8
506.5	6.19	58.46	1504.9
507.0	6.26	61.57	1680.6
507.5	6.33	64.72	1862.6
508.0	6.41	67.90	2050.8
508.5	6.48	71.12	2245.0
509.0	6.55	74.38	2444.9
509.5	6.63	77.67	2650.5
510.0	6.70	81.01	2861.6

Appendix B

Memorandum: Investigation of Differences Between Study Phase II and Study Phase III Results

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Memo

To:	Morgan Byars, P.E., City of Austin Watershed Protection		
From:	Scott Muchard, Texas P.E. No. 89409, HDR Engineering, Inc.	Project:	Erosion Detention Study - Phase III
CC:	Eric Stewart, P.E., HDR Engineering, Inc. Kelly Kaatz, P.E., HDR Engineering, Inc.		
Date:	January 14, 2011	Job No:	94889

Re.: Investigation of Differences Between Study Phase II and Study Phase III Results

Introduction

Phase II of the Erosion Detention Study examined the effectiveness of various pond design criteria in reducing erosion potential using long term continuous simulation (LTCS) hydrologic modeling. The pond designs studied in Phase II were based on criteria used by the City of Austin (COA) and/or suggested by others in the literature. Pond performance was assessed by computing the excess stream power (ESP) erosion index value associated with the LTCS time series of pond discharges (pond discharge hydrograph). The LTCS were computed with the U.S. Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) software. The Phase II work indicated that the standard COA 0.5 inch plus 0.1 inch water quality volume criteria[1] may provide more protection than is necessary to control erosion at impervious cover levels less than approximately 50% and less protection than is necessary at impervious cover levels greater than approximately 50%.[2]

Phase III of the study developed a stream protection volume criterion for which post-development ESP values, based on LTCS, match predevelopment levels. The stream protection volume criterion is expressed as a curve relating required pond storage volume to watershed percent impervious cover, specifying the required runoff volume to be captured and released over a 48-hour period. The final curve indicates that the COA standard water quality volume provides more storage than is necessary to match predevelopment erosion potential as quantified by ESP for all but the highest levels of impervious cover (above approximately 92%). In showing that the COA standard water quality volume provides more protection than is necessary over a wider range of impervious cover levels, the results of Phase III differ from those of Phase II.[3]

The methodology used to compute the ESP values varied little from Phase II to Phase III. Both studies used the same 15-year rainfall record in the LTCS hydrologic model, both used the same 100-acre hypothetical watershed at various impervious cover levels, and both used the same receiving stream characteristics (e.g., cross section, slope, bed material, etc.). However, two elements of the methodology differed between the two phases:

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[1] The COA standard water quality volume is the first 0.5 inch of runoff plus an additional 0.1 inch for each 10% increase of gross impervious cover over 20% within the drainage area to the control.

[2] HDR Engineering, Inc in association with Kurkjian Engineering Corporation, *Quantification of the Long-Term Benefits of On-Site Erosion Detention for Developing Austin Watersheds*, January 2007.

[3] HDR Engineering, Inc in association with Kurkjian Engineering Corporation, *Quantification of the Long-Term Benefits of On-Site Erosion Detention for Developing Austin Watershed: Stream Protection Curve*, Draft Report, March 2009.

1. Detention pond design is typically performed based on standard single event design storms of certain return periods as opposed to LTCS modeling. The design storm modeling is often carried out using the U.S. Department of Agriculture (USDA) National Resources Conservation Service (NRCS) Curve Number (CN) methodology to compute excess rainfall (runoff) along with the NRCS unit hydrograph methodology to transform excess precipitation to a runoff hydrograph. The CN method has limitations associated with its use in LTCS, particularly in that the loss rate asymptotically approaches zero instead of a constant dictated by soil infiltration characteristics. Because of this, the Horton infiltration method was used in the Erosion Detention study LTCS. In addition, SWMM does not use the NRCS unit hydrograph method to compute hydrographs. Therefore, in order to obtain a LTCS model that would produce design storm results that are consistent with a single event model that uses the NRCS CN and unit hydrograph methodologies, the SWMM model was "calibrated" or adjusted so that the hydrograph peak and volumes for several design storm events approximated those produced by a single event model. For Phase II, the calibration was based on 3-hour duration design storms simulated with the NRCS TR-20 model. The 3-hour storm was the standard COA design storm duration at the time the study was initiated. Between the initiation of the study and the beginning of Phase III, the City adopted the 24-hour NRCS Type III design storm. Thus, for Phase III of the project, the SWMM models were recalibrated to 24-hour duration design storms.

2. EPA SWMM Version 5.0.007 was used in conducting the Phase II work, which was the current version of the software at the time the study was initiated. When work began on Phase III, Version 5.0.013 of the software was available, and this updated version of the software was implemented.

We have completed additional evaluations to assess why the Phase III results indicate that the COA standard water quality volume provides better erosion mitigation than was expected based on the Phase II results. Effort was focused on examining the effects of the above noted methodology differences. This memorandum summarizes the findings of the additional work.

<u>SWMM Calibration Overview</u>

Table 3-4 of the Phase III draft report lists the calibrated SWMM parameters from Phases II and III of the study. The table is repeated below as Table 1.

As shown in Table 1, the watershed parameters that were changed between Phases II and III were the overland flow width, the Horton maximum infiltration rate, and the Horton minimum infiltration rate. As indicated in the Phase II and Phase III reports, the correlation of the overland flow width parameter to physical watershed characteristics is not absolute. In addition, hydrograph peak discharges are sensitive to this parameter. Given its ambiguity and the sensitivity of the hydrograph peaks to the parameter, the overland flow width was used as a calibration parameter and was adjusted to aid in matching hydrograph peaks. As mentioned in the Phase III report, the 24-hour SWMM design storm hydrograph peaks overestimate those of the TR-20 model for the 100-year event but underestimate them for the 2-year event by a approximately the same error percentage. Therefore, the calibrated overland flow width parameters selected for Phase III were considered to be optimal.

Table 1.
Calibrated SWMM Watershed Parameters

Parameter	**Value Used with 3-Hour Design Storm**	**Value Used with 24-Hour Design Storm**
Overland Flow Width, 5% Impervious Cover Watershed (ft)	**2500**	**2850**
Overland Flow Width, 20% Impervious Cover Watershed (ft)	**1750**	**3175**
Overland Flow Width, 50% Impervious Cover Watershed (ft)	**750**	**1275**
Overland Flow Width, 75% Impervious Cover Watershed (ft)	**750**	**1000**
Overland Flow Width, 100% Impervious Cover Watershed (ft)	**NA**	**2100**
Average Surface Slope (%)	1.5	1.5
Manning n for Impervious Cover	0.014	0.014
Manning n for Pervious Cover	0.15	0.15
Depth of Depression Storage on Impervious Areas (in)	0.03	0.03
Depth of Depression Storage on Pervious Areas (in)	0.2	0.2
Percent of Impervious Area with No Depression Storage	50	50
Percent of Runoff Routed Between Sub-areas	100	100
Horton Infiltration Parameters		
Maximum Infiltration Rate (in/hr)	**2.0**	**1.5**
Minimum Infiltration Rate (in/hr)	**0.5**	**0.15**
Decay Constant (1/hr)	5	5
Drying Time (days)	2	2

Both the Horton maximum and minimum infiltration rate parameters were lower in Phase III than in Phase II. As mentioned in the Phase III report, reducing these infiltration rate parameters was necessary to calibrate to the 24-hour TR-20 runoff volumes. Of particular importance was reducing the minimum rate parameter, the effect of which is more pronounced with storms of greater duration because the minimum infiltration rate establishes the asymptotic value of the infiltration curve. As also mentioned in the Phase III report, the Phase III minimum infiltration rate value is consistent with the literature values for Hydrologic Group C soils[4], which were assumed when selecting the TR-20 CN values for the 100-acre hypothetical watershed.

The effect of the difference in the calibrated Horton infiltration parameters is evident in the resulting infiltration rate curves (Figure 1). With lower maximum and minimum infiltration rate constants, the Phase III curve lies below the Phase II curve, producing about half as much infiltration over a 24-hour period (assuming rainfall is not limiting). Given the differences in the infiltration parameters between the two study phases, the differences in the SWMM results should be reflective of less infiltration and more runoff.

To explore these differences, a number of additional SWMM simulations were made to verify that differences in peak discharges, total discharges, and ESP values produced with the 3-hour design storm calibration parameters of Phase II and the 24-hour design storm calibration parameters of Phase III are reflective of the infiltration rate differences. The additional simulations were also

[4]Musgrave, G.W., "How Much Water Enters the Soils," U.S.D.A. Yearbook, U.S. Department of Agriculture, Washington, DC, 1955, pp. 151-159, cited in XPSWMM User's Manual access online at http://www.xpsoftware.com.au/products/swmm/webhelp/xpswmm.htm, January 8, 2009.

targeted at attempting to ascertain how the calibration variations between the two phases relate to the improved pond performance observed in Phase III.

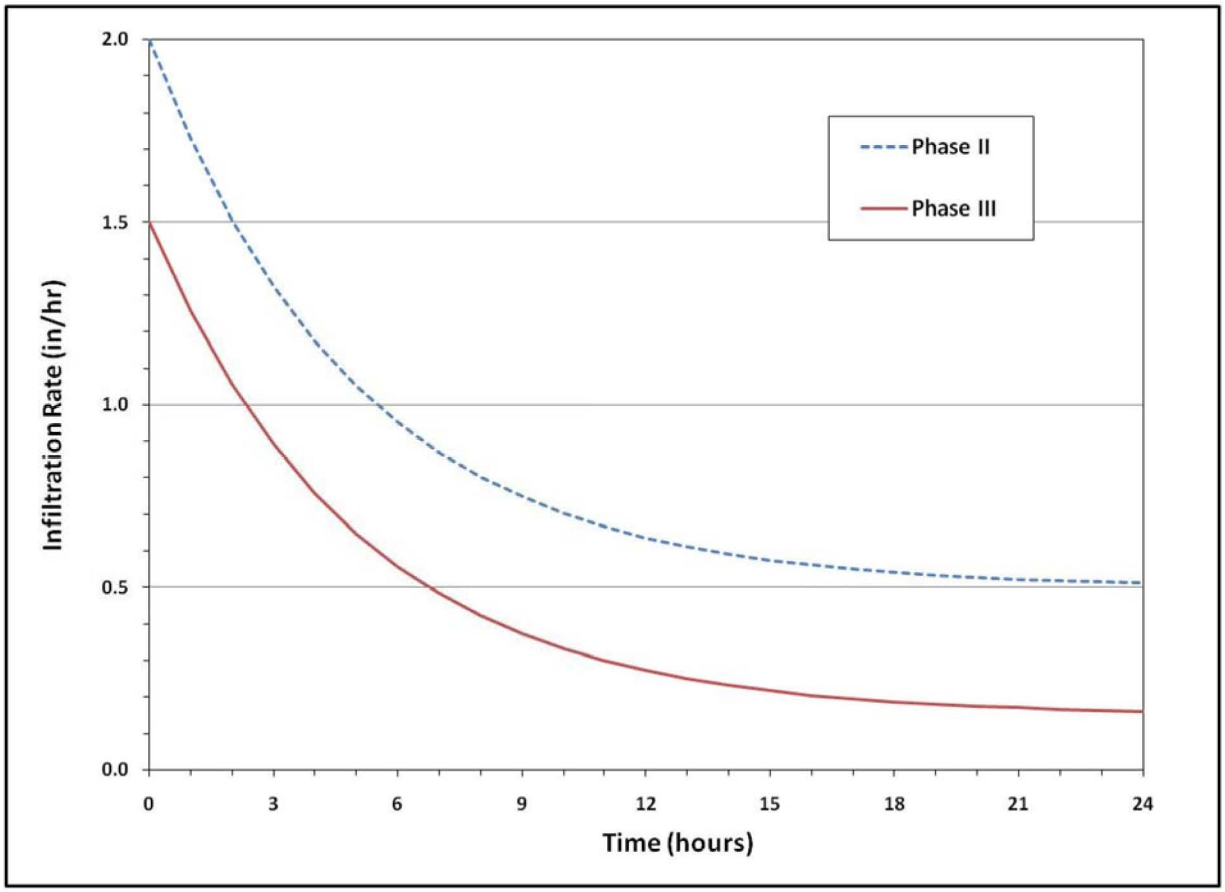

Figure 1. Comparison of Horton Infiltration Rate Curves for Phase II and Phase III

3-Hour and 24-Hour Design Storms Simulated in SWMM

Given the decreased infiltration associated with the 24-hour storm calibration of Phase III, it would be expected that any design storm simulated in SWMM with the 24-hour calibration would produce higher total runoff volume than the same storm simulated with the 3-hour storm calibration of Phase II. It also might be expected that due to the decrease in infiltration, the 24-hour calibration would produce higher peak discharges.

To verify these assertions, 3-hour and 24-hour design storms were simulated in SWMM, with each storm being executed using both the Phase II and Phase III calibration parameters. These simulations did not include detention ponds; they included only the 100-acre hypothetical watershed. Three levels of watershed impervious cover were evaluated: 5%, 50%, and 75%. The resulting peak and total discharges for the hypothetical watershed are summarized in Table 2. The values listed in Table 2 were produced with SWMM Version 5.0.013, and therefore there is some variation in the 3-hour calibration results compared to those provided in the Phase II report. The effects of the SWMM version are discussed later in this memorandum.

It is evident from the information provided in Table 2 that the 24-hour calibration of Phase III does in fact produce greater total runoff and higher peak discharges than the 3-hour calibration for a given rainfall event. Table 2 summarizes the percent increase in the peak discharge and total volume for a given storm computed with the 24-hour calibration compared to the 3-hour calibration.

Table 2.
Design Storm Simulation Results

Watershed Impervious Cover	SWMM Simulation	Peak Dis-charge (cfs)	Total Runoff Volume (acft)	Increase in Peak Discharge for 24-Hr Calibration Compared to 3-Hr Calibration (%)	Increase in Volume for 24-Hr Calibration Compared to 3-Hr Calibration (%)
5%	2-Yr 3-Hr Storm with 3-Hr (Phase II) Calibration	63.6	5.9		
5%	2-Yr 3-Hr Storm with 24-Hr (Phase III) Calibration	93.3	11.5	47	96
5%	2-Yr 24-Hr Storm with 3-Hr (Phase II) Calibration	27.6	3.3		
5%	2-Yr 24-Hr Storm with 24-Hr (Phase III) Calibration	55.9	10.1	102	209
5%	100-Yr 3-Hr Storm with 3-Hr (Phase II) Calibration	315.1	34.1		
5%	100-Yr 3-Hr Storm with 24-Hr (Phase III) Calibration	394.0	44.9	25	31
5%	100-Yr 24-Hr Storm with 3-Hr (Phase II) Calibration	257.7	33.0		
5%	100-Yr 24-Hr Storm with 24-Hr (Phase III) Calibration	366.9	56.3	42	71
50%	2-Yr 3-Hr Storm with 3-Hr (Phase II) Calibration	185.1	12.5		
50%	2-Yr 3-Hr Storm with 24-Hr (Phase III) Calibration	234.3	16.0	27	28
50%	2-Yr 24-Hr Storm with 3-Hr (Phase II) Calibration	98.2	14.9		
50%	2-Yr 24-Hr Storm with 24-Hr (Phase III) Calibration	128.9	18.7	31	25
50%	100-Yr 3-Hr Storm with 3-Hr (Phase II) Calibration	493.1	43.0		
50%	100-Yr 3-Hr Storm with 24-Hr (Phase III) Calibration	600.6	50.1	22	17
50%	100-Yr 24-Hr Storm with 3-Hr (Phase II) Calibration	419.0	56.4		
50%	100-Yr 24-Hr Storm with 24-Hr (Phase III) Calibration	545.7	69.8	30	24
75%	2-Yr 3-Hr Storm with 3-Hr (Phase II) Calibration	228.6	17.1		
75%	2-Yr 3-Hr Storm with 24-Hr (Phase III) Calibration	270.0	18.8	18	10
75%	2-Yr 24-Hr Storm with 3-Hr (Phase II) Calibration	128.0	21.9		
75%	2-Yr 24-Hr Storm with 24-Hr (Phase III) Calibration	149.1	23.8	17	9
75%	100-Yr 3-Hr Storm with 3-Hr (Phase II) Calibration	628.5	50.6		
75%	100-Yr 3-Hr Storm with 24-Hr (Phase III) Calibration	703.3	53.6	12	6
75%	100-Yr 24-Hr Storm with 3-Hr (Phase II) Calibration	529.2	71.4		
75%	100-Yr 24-Hr Storm with 24-Hr (Phase III) Calibration	610.8	77.5	15	9

Note: Design storm simulations conducted with SWMM Version 5.0.013.

Of note in Table 2 is that the percent increase in peak discharge and total runoff volume associated with the 24-hour calibration decreases with increased impervious cover. For example, the percent increase in total runoff volume for the 2-year 3-hour storm with the 5 % impervious cover watershed is 96%, while it is only 10% for same storm with the 75% impervious cover watershed. So the difference in the two calibrations is less prominent at higher impervious cover levels than at lower impervious cover levels. This is consistent with the infiltration parameters only affecting the pervious portion of the watershed; changing these parameters has less of an effect on watersheds with less pervious cover. As discussed further below, the variation of the effect of the calibration with impervious cover has implications on the evaluation of pond performance based on ESP values.

Uncontrolled Watershed ESP Values

LTCS ESP values were computed for the 100-acre hypothetical watershed at various levels of impervious cover to assess the effect of the Phase II and Phase III calibration differences on the LTCS runoff hydrographs. The objective was to evaluate how the level of mitigation required of the ponds changed with the change in the SWMM calibration. Since, pursuant to the study methodology, a pond volume is considered to mitigate the effects of development if the ESP value computed from the pond outflow hygrograph is equal to or less than the ESP value for the undeveloped watershed (assumed to be 5% impervious) runoff hydrograph, the mitigation level required of a pond can be measured by comparing the ESP for the runoff from a developed watershed to that of the undeveloped watershed.

LTCS simulations were run for the 5%, 20%, 50%, and 75% impervious cover watersheds and the ESP values were computed directly from the watershed runoff hydrographs. The resulting ESP values are summarized in Table 3. The values listed in Table 3 were produced with SWMM Version 5.0.013, and therefore there is some variation in the 3-hour calibration results compared to those provided in the Phase II report. The effects of the SWMM version are discussed later in this memorandum.

Table 3.
Uncontrolled Watershed ESP Values

Impervious Cover (IC)	3-Hr Phase II Calibration: Uncontrolled Watershed ESP Value	3-Hr Phase II Calibration: Ratio of ESP Value to 5% IC ESP Value	24-Hr Phase III Calibration: Uncontrolled Watershed ESP Value	24-Hr Phase III Calibration: Ratio of ESP Value to 5% IC ESP Value	Ratio of 24-Hr Calibration ESP to 3-Hr Calibration ESP
5%	251	1.0	806	1.0	3.2
20%	776	3.1	1354	1.7	1.7
50%	1811	7.2	2266	2.8	1.3
75%	2865	11.4	3109	3.9	1.1

Note: LTCS conducted with SWMM Version 5.0.013.

The ESP values listed in Table 3 show that, at all impervious cover levels, the ESP values for the uncontrolled watersheds are higher for the 24-hour calibration than for the 3-hour calibration. This is consistent with the increased design storm peak runoff rates and runoff volumes that are associated with the 24-hour calibration infiltration parameters. The last column in Table 3 provides the ratio of the 24-hour calibration ESP value to the 3-hour calibration ESP value and shows that the relative difference between the two decreases with increased impervious cover. This is consistent with the impervious cover trends in the design storm peak runoff rate and runoff volume that were identified in the previous section of this memorandum.

The third and fifth columns of Table 3 list the ratio of the ESP value to that of the undeveloped (5% impervious cover) watershed. For the 3-hour calibration, the 75% impervious cover uncontrolled watershed produces an ESP value over 11 times greater than that of the undeveloped (5% impervious cover) watershed. For the 24-hour calibration, the 75% impervious cover uncontrolled watershed produces an ESP value that is slightly less than 4 times greater than that of the undeveloped watershed. This indicates that, for the 24-hour calibration, detention ponds need to do less to mitigate the watershed runoff erosion potential to predevelopment levels. As a corollary of this, a pond of a given volume would be expected to show better performance in terms of its ability to reduce ESP values to the pre-developed condition when evaluated with the 24-hour calibration than when evaluated with the 3-hour calibration. This assertion is explored further in the following section.

Standard Water Quality Pond ESP Values

The three ponds from Phase II of the study designed according to the standard COA 0.5 inch plus 0.1 inch water quality volume criteria with a 48-hour drawdown time were simulated with SWMM Version 5.0.013. The ponds were designed to control runoff from the 20%, 50%, and 75% impervious cover watersheds, and the pond storage volumes increase with increasing impervious cover level. The simulations were conducted with both the 3-hour and 24-hour SWMM calibrations. The ESP value resulting from each pond's discharge hydrograph was computed and is listed in Table 4. Values for the undeveloped (5% impervious cover), uncontrolled watershed are included in the last row of the table for reference.

Table 4.
COA Standard Water Quality Pond ESP Values

Simulation	Pond Volume Excluding Overflow Volume (acft)	3-Hr Phase II Calibration ESP	24-Hr Phase III Calibration ESP
1/2" + 0.1" WQ Volume, 48-Hour Release, 20% IC Watershed	4.17	137	524
1/2" + 0.1" WQ Volume, 48-Hour Release, 50% IC Watershed	6.67	300	582
1/2" + 0.1" WQ Volume, 48-Hour Release, 75% IC Watershed	8.75	535	694
Undeveloped (5%IC) Uncontrolled (no pond) Watershed	NA	251	806

Note: LTCS conducted with SWMM Version 5.0.013.

Table 4 shows that the 24-hour calibration ESP values exceed the 3-hour calibration for each of the watersheds simulated. This is expected based on the reduced infiltration rates associated with the 24-hour calibration and is consistent with the design storm results presented in this memorandum. Comparing the ESP values computed for the 20%, 50%, and 75% impervious cover watersheds to those computed for the undeveloped, uncontrolled watershed indicates whether the ponds are mitigating erosion potential to the pre-development level. For the 3-hour Phase II calibration, the results show that the COA standard water quality pond volume mitigates erosion potential to below pre-development levels for the 20% impervious cover watershed, but that the COA standard water quality volume for the 50% and 75% impervious cover levels does not. When assessed using the SWMM model with the 24-hour Phase III calibration, the COA standard water quality criteria control erosion potential to below pre-development levels at all three impervious cover percentages.

Comparison of the 3-hour and 24-hour ESP values shown in Table 4 supports the Phase III finding that the COA standard water quality volume mitigates erosion over a broader range of impervious cover levels than indicated in Phase II.

Phase II Versus Phase III Ponds

As a final verification of the Phase III work, several ponds of similar volume from Phases II and III were simulated in controlling runoff from the same watershed using LTCS. The goal of this exercise was to demonstrate that the pond design parameters (e.g., outlet design, pond geometry, etc.) used in Phase III were consistent with those used in Phase II. With consistent design parameters, ponds of similar volume from each study should produce similar ESP results when receiving runoff from the same watershed.

Table 5 summarizes the additional simulations that were completed to verify the pond design parameters. The three standard COA water quality volume ponds with 48-hour drawdown time discussed in the previous section of this memorandum were used again in these simulations. The volumes of these ponds are listed in Table 5 along with the ESP values for the pond outflow hydrographs computed with SWMM Version 5.0.013 and the 24-hour watershed calibration parameters. The three ponds from Phase III having volumes closest to those of the three ponds from Phase II were identified. The Phase III pond closest in volume to the 20% impervious cover Phase II standard COA water quality pond was simulated with a 20% impervious cover watershed, the Phase III pond closest in volume to the 50% impervious cover Phase II standard COA water quality pond was simulated with a 50% impervious cover watershed, and the Phase III pond closest in volume to the 75% impervious cover Phase II standard COA water quality pond was simulated with a 75% impervious cover watershed. These LTCS again used SWMM Version 5.0.013 and the 24-hour watershed calibration parameters. The selected ponds from Phase III, their volumes, and ESP values resulting from the LTCS are included in Table 5.

The ESP values in Table 5 show that ponds from Phase III having volumes similar to the COA standard water quality volume ponds of Phase II produce similar results. In the case where the Phase III pond is slightly larger than the Phase II pond, the Phase III Pond ESP is slightly lower, and in the cases where the Phase III pond is slightly smaller than the Phase II pond, the ESP is slightly higher, as would be expected. Overall the ESP results in Table 5 verify that the pond design parameters used in the two study phases were consistent.

Table 5.
ESP Values for Comparable Phase II and Phase III Ponds

Standard Water Quality Volume Ponds from Phase II			Comparable Phase III Ponds		
Standard Water Quality Volume Pond ID	**Volume Excluding Overflow Volume (acft)**	**ESP (24Hr Phase III Calibration)**	**Comparable Phase III Pond ID**	**Volume Excluding Overflow Volume (acft)**	**ESP (24Hr Phase III Calibration)**
1/2" + 0.1" WQ Volume, 48-Hour Release, 20% IC Watershed	4.17	524	30% IC 115% Vol	4.29	502
1/2" + 0.1" WQ Volume, 48-Hour Release, 50% IC Watershed	6.67	582	60% IC 70% Vol	6.29	632
1/2" + .1" WQ Volume, 48-Hour Release, 75% IC Watershed	8.75	694	60%IC 95% Vol	8.54	736

Note: LTCS conducted with SWMM Version 5.0.013.

SWMM Version

The SWMM modeling for Phase II of the study was conducted using EPA SWMM Version 5.0.007, which was the current version when the study was initiated. When the Phase III work began, Version 5.0.013 was available, and this updated version was implemented. The SWMM update history documentation includes the following note on a change related to the Horton infiltration model that was made between versions 5.0.007 and 5.0.008 and may be relevant to the Erosion Detention study:

> The conversion from the Horton infiltration drying time input parameter to an equivalent regeneration curve constant was corrected.[5]

As an assessment of the effect of the differing model versions on the study conclusions, the LTCS for the COA standard water quality ponds summarized in Table 4 were repeated with SWMM Version 5.0.007. The results are summarized in Table 6. Comparison of the ESP values in the Table 6 to those in Table 4 shows that the two different versions of SWMM do produce variations in the ESP values. However, the conclusions to be drawn regarding the performance of the COA standard water quality volume are generally the same whether evaluated with SWMM Version 5.0.007 or 5.0.013. Specifically, when evaluated with the 3-hour calibration, the COA standard water quality volume appears to over-control at lower impervious cover levels, but appears to provide insufficient mitigation at higher impervious cover levels. With the 24-hour calibration, the simulation results show that the standard water quality volume controls erosion to predevelopment conditions or less over a broader range of impervious cover levels.

[5]U.S. EPA, *SWMM 5.0 Update History*, text file accompanying install files for SWMM Version 5.0.013 released March 11, 2008.

Table 6.
COA Standard Water Quality Pond ESP Values Computed with SWMM 5.0.007

Simulation	Pond Volume Excluding Overflow Volume (acft)	3-Hr Phase II Calibration ESP	24-Hr Phase III Calibration ESP
1/2" + 0.1" WQ Volume, 48-Hour Release, 20% IC Watershed	4.17	160	636
1/2" + 0.1" WQ Volume, 48-Hour Release, 50% IC Watershed	6.67	317	640
1/2" + 0.1" WQ Volume, 48-Hour Release, 75% IC Watershed	8.75	549	731
Undeveloped (5%IC) Uncontrolled (no pond) Watershed	NA	326	1043

Summary and Conclusion

The methodology used to compute the ESP values varied little from Phase II to Phase III of the study. However, the two elements of the methodology that differed were the SWMM calibration parameters and the SWMM software version used. We have examined how these two methodology differences impacted the conclusions presented in both phases of the study regarding the effectiveness of the COA standard water quality volume in controlling erosion potential as measured by the ESP erosion index computed with LTCS of a hypothetical 100-acre watershed. The variation in results from the two phases is consistent with the difference in the calibrated Horton infiltration parameters used in the two phases. Although the different versions of SWMM used in the two phases do produce variations in the ESP results, similar conclusions regarding the effectiveness of the ponds would be drawn based on simulations executed with SWMM Version 5.0.007 or with Version 5.0.013. We conclude that the difference in the model calibration, particularly the infiltration parameters, is the principal factor that lead to the COA standard water quality volume showing effectiveness over a broader range of impervious cover levels in Phase III than in Phase II.